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Life-Cycle Analysis of Aircraft Turbine Engines

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J. R. Nelson

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The report presents a methodology enabling the weapon-system planner to acquire early visibility of cost magnitudes, proportions, and trends associated with a new engine's life cycle, and to identify "drivers" that increase cost and can have the effect of lowering capability. Later in the life cycle, logistics managers can use the methodology and the feedback it produces for more effective system management. The procedure followed was to: develop a theoretical framework for each phase of the life cycle; collect and analyze data for each phase; develop parametric cost-estimating relationships (CERs) for each phase; use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends, and to identify cost-drivers and their effects; and examine commercial experience for cost data and operational and maintenance practices that could be profitable for the Air Force. Refs. (WH)

PREFACE

This report presents the findings of a Rand analysis of the life cycle of aircraft turbine engines. Application of the methodology developed in the study should aid decisionmakers by yielding useful insights into the life-cycle process not only for engines but for other aerospace equipment as well. The study was undertaken as part of the project "Methods and Applications of Life-Cycle Analysis for Air Force Systems," sponsored by Project AIR FORCE (formerly Project RAND) and conducted initially within the R&D and Acquisition Program and later within the Logistics Program at Rand. The work was performed during 1975 and early 1976 using data current as of 1974. A progress report was widely briefed during 1976 and early 1977, followed by publication of a short executive summary: R-2103/1-AF, *Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary*, by J. R. Nelson, March 1977.

Expanding on earlier Rand efforts in weapon-system life-cycle analysis[1] and aircraft turbine engine state-of-the-art assessment and acquisition cost estimation,[2] the present study examines the life-cycle process for this important subsystem in the hope that findings previously obtained at the weapon-system level can be corroborated and policy issues clarified.

The report discusses the acquisition and ownership phases of the military engine life-cycle process, the data available for analysis, and the model-development and application results for each phase. Commercial life-cycle practice is reviewed for lessons that might be applicable to military practice. The report should be of interest to offices at Hq USAF, the Air Force Systems Command, and the Air Force Logistics Command, where quality and cost tradeoffs during a weapon-system life cycle and the effects of such tradeoffs on meeting a military mission in an era of increasing budget constraints are matters of close concern.

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[1] J. R. Nelson et al., *A Weapon System Life-Cycle Overview: The A-7D Experience*, The Rand Corporation, R-1452-PR, October 1974; and M. R. Fiorello, *Estimating Life-Cycle Costs: A Case Study of the A-7D*, The Rand Corporation, R-1518-PR, February 1975.

[2] J. R. Nelson and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974.

SUMMARY

This report presents a methodology for life-cycle analysis of aircraft turbine engines, derived from the study of historical data; the data in some instances span 25 to 30 years, and in others only one or two years. The report also presents numerous findings—some of them surprising—that emerged from study of the data. The findings suggest ways to augment and improve the methodology in the future, and some of them should be of immediate utility to the Air Force for improving engine life-cycle cost estimates and acquisition and ownership practices. The study's governing objective is to enable the weapon-system planner to acquire early *visibility* of cost magnitudes, proportions, and trends associated with a new engine's life cycle and to identify "drivers" that increase cost and can have the effect of lowering capability.

The study was prompted by the fact that the costs of acquiring and owning turbine engines have escalated steadily over the years for both military and commercial users. Most of the causes are readily apparent. Demands for higher overall quality—meaning performance, primarily, for the military—have resulted in larger engines that produce greater thrust, run hotter, are costlier to maintain, and entail higher basic engine prices. Material costs associated with engine price have also risen rapidly in the recent past; over the long term, however, labor costs, primarily in the manufacturing sector, have risen proportionately more so.

The Air Force has long been aware of these facts, generally speaking; however, one of the major findings of this study is that engine ownership costs are much greater than, and different from, what anyone has previously realized. For example, it now appears that depot costs alone could exceed procurement costs for a new engine with a 15-year lifespan. (In this study, all costs are expressed in constant dollars. Discounting may change some findings, depending on the distribution of cost outlays over the time horizon of interest and the discount rate assumed.)

The chief problem confronting this study, as it has confronted past researchers, is the lack of disaggregated, homogeneous, longitudinal ownership data that are specific to particular engine types, notably at the Air Force base and depot level. The collection of such data will be necessary for perfecting the methodology, which weapon-system planners can then use to calculate the costs and benefits of a proposed engine for a new aircraft in the early stages of planning and selection; in later phases of the life cycle, logistics managers can use the methodology and the feedback it produces for more effective system management.

The procedure followed in this study was to: (1) develop a theoretical framework for each phase of the life cycle; (2) collect and analyze data for each phase; (3) develop parametric cost-estimating relationships (CERs) for each phase; (4) use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends, and to identify cost-drivers and their effects; and (5) examine commercial experience for cost data and operational and maintenance practices that could be profitable for the Air Force.

The CERs obtained include engine characteristics and schedule variables known to be important to each phase of the life cycle. They also include measures of the quality (benefit sought) and the state-of-the-art advance represented by a

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particular engine. In its fullest sense, quality embodies not only the performance measures emphasized by the military, but also durability, reliability, maintainability, safety, and concern for environmental effects, all of which are important to the commercial world. The overall balance among quality, schedule, and costs for an engine thus reflects the early planner's estimate of the utility of the product ultimately delivered to the user.

For a new military engine (acquired and owned under conditions similar to those with the previous engines constituting the data base) that will have an operational lifespan of 15 years, the findings indicate that:

- As mentioned above, engine ownership costs are significantly larger than and different from those found in previously published studies. For instance, engine depot and base maintenance costs, not including fuel and attrition, can exceed engine acquisition costs. This finding is true for current fighter and transport engines.
- Depot costs alone can exceed procurement costs.
- Component improvement programs (CIP) conducted during the operational life of an engine can cost as much as it did to develop the engine to its initial model qualification. A difficulty encountered in this area has been the aggregate nature of the CIP funds. Prior to 1969, CIP funding did not separate performance growth and additional engine applications from correction of deficiencies, reliability enhancement, cost reduction, and repair procedures. Consequently, this study has not been able to ascertain specifically the cost of some magnitude of reliability improvement during an engine's maturation. (The models can be used, however, to estimate the ownership cost reduction expected by improving the actual and maximum times between overhaul.)
- If component improvement and whole spare engine procurement are considered ownership costs, then ownership currently constitutes at least two-thirds of total engine life-cycle cost. This is true for current supersonic fighter and subsonic transport/bomber engines.
- Satisfying results, in terms of statistical quality, theoretical behavior, and experience from past programs, were obtained from modeling performance/schedule/cost relationships for the development and production of military engines; the statistics were highly significant and the positive and negative signs for the variables occurred as one would expect from theoretical considerations and actual experience. Mixed but promising results were obtained in modeling ownership costs for military engines. Depot maintenance costs were more detailed and amenable to analysis than base maintenance costs. Because both the depot and base models were derived with sparse data, however, they must be used cautiously until better data and thus improved models become available.
- Application of the models obtained in this study indicates that there is a continuing trend in the direction of higher ownership costs, measured in both absolute dollars and as a percentage of total life-cycle costs. Increasing depot cost is the primary reason for this trend. The production cost of the engine (and its parts) is a contributor to depot and base support costs, but so are ownership policies. To alter the depot cost trend, the Air Force will have to depart significantly from its current ownership practices at

both depots and bases. The study identifies operational and support policies and procedures that should be strongly supported in attempting to break the trend. Recent efforts with the F100 engine concerning modular design, on-condition maintenance, engine diagnostics, and power management are directed toward counteracting the trend and merit vigorous support. But other policies and procedures beyond the scope of this study are also important.

- Acquisition and ownership costs for engines currently in the Air Force inventory can vary by an order of magnitude between engine programs and applications; these costs are affected by the engine quality and mission desired, the schedule imposed on new-engine acquisition, and the operating and support policies selected.
- The engine maturation process must be more fully understood if improved analytical results are to be obtained and applied to new-engine selection. It takes an engine a long time to mature (commercial experience indicates five to seven years). Consequently, average ownership costs are significantly higher during that period than mature-engine steady-state costs in terms of dollars per flying hour, the yardstick most commonly used.

To take full advantage of the methodology described here, the study recommends that the Air Force:

- Begin collecting and *preserving* disaggregated, homogeneous, longitudinal data at both depots and bases, associated with specific engine types. Currently, efforts have just begun to separate base maintenance costs by weapon system; and studies of total depot costs for engines do not consistently include, along with overhaul of whole engines, the cost of parts repair during overhaul, the cost of expendable parts, the full cost of replacing condemned reparables, the full cost of modification hardware, and the repair of components received directly from the field and returned to the field.
- Use the methodology in its current form to estimate the costs of future engines (that is, of any engines that are acquired in the same manner as in the past), and to measure how costs might change if acquisition and ownership were conducted differently; and update the methodology as new data become available.
- Supplement the engine flying hour as the principal measure of the costs of ownership with other outputs such as sorties, takeoffs and landings, engine throttle excursions, and calendar time. With the advent of higher fuel costs, the Air Force may elect to compress flying training into fewer flying hours; if it does so, the total cost of flying may not necessarily show a decrease because the cost of a sortie may remain the same or even increase.

The Air Force may also wish to consider the following actions, for some of which the rationale derives from commercial experience:

- Expand the awareness of what is entailed for the modular approach to engine design, which is already common in some commercial engines and is beginning to appear in military engines. Modular design apparently expedites and lowers the cost of maintenance, but requires certain actions which, if not accomplished, can negate at least in part some of the expected benefits.

- Monitor full-throttle excursions; even a nominal reduction in hot-time may significantly improve parts life. The F100 engine on the F-15 has an excursion counter, but it is not yet working very well; the new Engine Diagnostic System for the F100 could be extremely beneficial.
- Support efforts to move more in the direction of commercial-style on-condition maintenance, in an attempt to extend the intervals for average time between overhaul (ATBO) and determine the appropriate work to be done when an engine is returned to the depot. Such a move must be tempered by Air Force policy and Air Force experience.
- Carefully define "quality" and costs in the early phases of weapon system planning. Performance may well continue to be the dominant aspect of quality for the military; but planners should be able to answer such questions as, for example, whether the aircraft's mission makes it worth it to strive for an extra increment of engine performance if the penalty may be greater downtime and additional spare engine and parts procurement, and thus higher overall acquisition and ownership costs. While the technique presented in the study is applicable at the engine subsystem level, final design decisions must be related to the engine's impact on the system, wherein other considerations such as mission effectiveness, attrition, fuel consumption, and aircraft and installation design characteristics must be weighed and given proper recognition.

When improved and backed up with proper data, the methodology presented here should supply valuable information with which the initial tradeoffs for the engine can be evaluated.

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SYMBOLS

ATBO = Average time between overhaul, hours
CIP = Component improvement program cost, millions of 1975 dollars
CPUSP = Current production unit selling price, thousands of 1975 dollars
DMQTC = Development cost to MQT, millions of 1975 dollars
DEVTIME = Development time from start to MQT, calendar quarters
EFH = Engine flying hour
EFHC = Engine flying hour consumed by operating fleet
EFHR = Engine flying hour restored to fleet by depot maintenance
KPRATE = Average production rate, 1000 engines/quarter[1]
KPUSP = 1000th unit production cost, millions of 1975 dollars
LCC = Life-cycle cost
MACH = Maximum flight envelope Mach number (measure of speed related to speed of sound)
MCDUM = Military-commercial dummy (1 = commercial, 0 = military)
MFRDUM = Manufacturer dummy (1 = Pratt & Whitney, 0 = others)
MQT = Model Qualification Test
MQTQTR = Man-rated 150-hr Model Qualification Test date, calendar quarters (October 1942 = 1)
MQTY = Total quantity produced, millions of units
MTBO = Maximum time between overhaul, hours
MVOLUME = Engine volume (max. dia. and length, cu. in./10^6)
OPSPAN = Time since operational use began, quarters
PRQTYC = Production quantity cumulative cost at quantity purchased, millions of 1975 dollars
QMAX = Maximum dynamic pressure in flight envelope, lb/ft^2
QTY = Quantity of production engines procured
RDT&E = Research, development, test, and evaluation
RMS = Resource Management System
SFCMIL = Specific fuel consumption at military thrust, sea-level static (SLS), lb/hr/lb thrust
TEMP = Maximum turbine inlet temperature °R
THRMAX = Maximum thrust (with afterburner if afterburner configuration), SLS, lb
TOA = Time of arrival

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[1] Several variables are expressed in what appear to be unusual units in order to obtain significant figures in the computer outpout for various equations.

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TOA26	Time of arrival of demonstrated performance obtained from model derived using 26 military turbojet and turbofan engines, calendar quarters
TOA37	Time of arrival of demonstrated performance obtained from model derived using 26 military and 11 commercial turbojet and turbofan engines, calendar quarters
ΔTOA26U	TOA26-MQTQTR, calendar quarters
TDC	Total development cost including MQT and product improvement, millions of 1975 dollars
TOTPRS	Pressure term (product of QMAX x pressure ratio), lb/ft^2
WGT	Weight of engine at configuration of interest, lb

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CHAPTER 1

INTRODUCTION

For we know in part, and we prophesy in part. -
1 Cor. 13:9

Over the past decade, the Department of Defense has placed increasing emphasis on understanding and assessing acquisition strategies and cost considerations in the development and procurement of new weapon systems. In the present era of budget constraints, and with an increasing share of the DoD budget devoted to operating and supporting forces in being, it has become even more important to be able to measure the contribution of both new and existing weapon systems to the overall defense posture—that is, their benefits relative to their costs.

It is important to link product cost to product benefits to be able to address the question: the cost of what? This is the objective of life-cycle analysis. For instance, the cost per unit of effectiveness for a new weapon system can be reduced by either lowering cost or increasing effectiveness, or by doing both. Aggregation of cost figures alone is not enough; the key is to understand total life-cyle cost in terms of its full magnitude, distribution among cost elements, and trends over time relative to the benefits to be obtained. to be obtained.

DoD officials have been concerned that, if current budget and cost trends continue, forces may not be able to modernize effectively or maintain effective peacetime training and readiness operations; that would degrade our war-fighting capability. This study is concerned with understanding the maintenance of a wartime capability in a peacetime environment, during which it can be difficult to justify what appear to be large defense budgets; the tenor of the times calls for careful cost allocation to maintain a balance between current operations and modernization. It also appears that, historically, it is in peacetime that operations and support budgets become large relative to acquisition budgets; and because weapon systems remain in the inventory longer during peacetime, operations and support account for a larger portion of the total life-cycle cost.

Consequently, attention has recently focused on attempts to understand and predict total life-cycle costs for new weapon systems and important subsystems, including aircraft turbine engines. Costs include not only those of acquisition (development and procurement) of a new weapon system, but also all the costs of operating and supporting the system in the field during its inventory lifetime. The latter costs, for both existing and proposed weapon systems, must be more clearly understood to make effective tradeoffs during new developments and procurements. These costs are now a fruitful area for investigation. The main difficulty confronting this study, as it has confronted previous researchers, is the unavailability of disaggregated, homogeneous, longitudinal data associated with specific engine types, particularly at the Air Force base and depot level. The data that are available are largely aggregated, heterogeneous, and cross-sectional, covering short periods of time; and commercial contractors are understandably reluctant to offer free access to certain proprietary cost information.

OBJECTIVE OF THE STUDY

This study of the life-cycle analysis of aircraft turbine engines has a two-fold objective: (1) to develop a methodology for assessing life-cycle benefits and costs; and (2) to apply that methodology to improve understanding of policy options for engine acquisition and ownership.

The problem addressed is the weapon-system planner's lack of detailed information and a methodology to enable him to make early decisions concerning the selection of a new engine within a life-cycle context. Accordingly, this report presents information and a methodology for life-cycle analysis, derived from the study of historical data on military and commercial engines, to provide a weapon-system planner an early analytical perspective. This methodology, when backed up with appropriate data collection, should equip the weapon-system planner with improved early *visibility* of the magnitudes, proportions, and trends of costs associated with the various phases of an engine's life cycle. He should then be able to identify influential parameters that drive costs and exert leverages between life-cycle phases, and thus be able to assess tradeoffs among quality, schedule, and cost in the search for policies appropriate to the various phases of a new engine's life cycle. The expected magnitude and proportion of ownership costs relative to total life-cycle costs has a direct bearing on early decisions.[1] If early policy decisions cannot affect a large part of the ownership costs later on, then there is little need to worry about such decisions. The planner may still want to spend additional money on development and on component improvement, so as to enhance the component's performance and reliability in the weapon system and thus increase operational capability. But concern about operations and support cost, if this is the relevant environment, would certainly be secondary, even from the outset of early planning.

The methodology can also serve as a *control* or feedback mechanism as the new system is developed, procured, and placed in operational service; the planner can use the information it provides to measure results obtained and use those results in estimating benefits and costs for the next system.

The major concern in this study, then, is to illuminate the entire life-cycle process for military aircraft turbine engines in terms of overall benefits and costs and their interactions. Commercial experience is also investigated to identify practices that the military might profitably adopt

Several broad questions will be addressed:

1. What are the magnitudes of life-cycle costs for the various kinds of aircraft turbine engines?
2. What are the cost elements and their distribution?
3. How have these elements' distributions changed over time?
4. Are costs driven by certain key parameters and can they be separated from other parameters to measure individual effects?
5. Are there interrelationships or tradeoffs between phases of the product's life or between characteristics of the product?
6. To what degree do policies and organizational behavior affect costs? Can relevant experience be obtained from study of commercial practices?

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[1] See App. A for one aerospace manufacturer's viewpoint on when, in the life cycle of a new weapon system, major influence is exerted on costs.

At least partial answers are sought in this study through the use of analytical techniques applied to available data. The procedure followed was to: (1) develop a theoretical framework for each phase of the life cycle, one feature of which was use of a technique for assessing the state-of-the-art advance represented by a new engine; (2) collect and analyze data for each phase; (3) develop and test parametric cost-estimating relationships (CERs) for each phase; (4) use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends[2] and to identify cost-drivers and their effects; and (5) examine commercial practice for cost data and operational and maintenance practices that might be profitable for the Air Force.

To the extent that this research is successful, it will provide system planners with a set of abstracted and generalized results to aid in policy formulation for future systems; in particular, an important outcome would be techniques to predict life-cycle benefits and costs, including the tradeoffs that may be made across life-cycle phases and system characteristics.

BACKGROUND

Aircraft turbine engines are a particularly promising subject for study because: (1) They are extremely important in weapon-system applications; (2) they are felt to be the pacing subsystem in aircraft weapon-system development; (3) they represent a large inventory and budgetary expense; (4) their 30-year history of continuing technological improvement furnishes a sizeable (though fragmentary) data base for analysis; and (5) they could provide insights, from a subsystem viewpoint, across the life-cycle spectrum, that may be readily applicable to the weapon-system level. The subject also has an immediate practical urgency: Engines are a topic of considerable interest today because of problems arising in the operational inventory with aircraft grounded owing to engine-related problems.

Previous Rand studies have dealt with aircraft turbine engines, and some of Rand's engine cost-estimating work goes back over a decade. More recently, this research has turned to the problem of measuring the state of the art in turbine engines and relating this measure to development and procurement costs in an attempt to evaluate tradeoffs in performance, schedule, and cost[1]. That methodology will be investigated in this study for possible extension to ownership cost, to assist in providing an overall methodology for estimating total life-cycle cost.

RESULTS OF PREVIOUS STUDIES

Many past studies have attempted to shed light on the engine life-cycle process, and current studies within the Air Force and the DoD community are extensively involved in life-cycle cost estimates. The central question is, How much does it cost to acquire and own a new military engine over its life cycle? No previous study has been able to answer that question fully. The two major problems involved are obviously: (1) accurately measuring what has already taken place; and (2) using such information to predict the future.

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[2] Use of this procedure implies that the future will behave like the past; consequently, the results here apply to a "will-cost" context rather than a "should-cost" context. "Should-cost" implies changing the structure and behavior of the current institutional arrangement. "Will-cost" entails the danger of being a self-fulfilling prophecy.

The most recent studies examined have been more qualitative than quantitative, or for the most part have addressed only a portion of the life cycle.[3] Some previous studies have attempted to quantify operating and support costs and total life-cycle costs for specific engines, but no study to date has clearly and consistently defined *all* of the relevant cost elements and obtained their associated actual costs for any ongoing engine program. Furthermore, no methodology has been provided for predicting costs for new engines over the entire life cycle. The lack of data is the persistent obstacle in the path. For existing engines in the USAF inventory, studies of operating and support costs have been performed with cross-sectional data; in most cases, they cover only a single fiscal year or even less. For a new engine, the procedure has been to select a closely similar existing engine and use modified cross-sectional data from that engine's current experience (usually at steady-state conditions) in an attempt to project operating costs over the proposed engine's entire life cycle. The combined lack of disaggregated, homogeneous, longitudinal data and of a reliable methodology for projecting detailed cost estimates over a new engine's life cycle have frustrated attempts to estimate life-cycle costs. Furthermore, none of these previous studies have attempted quantitative calculations of the effect of state-of-the-art advances on life-cycle costs.

All these difficulties have led earlier studies into the erroneous conclusion that engine base and depot maintenance costs are a relatively minor fraction of total life-cycle costs for an engine—as little as one-tenth to one-fifth, with the range being affected by whether or not fuel consumption attributed to a mission was considered within the total cost estimate.

These earlier studies suffered from the difficulty of defining the cost elements associated with each of the phases of the life cycle, and ascertaining whether these cost elements were consistent over time and whether all relevant cost elements were indeed included; their results further depended heavily on the data sources and assumptions they employed. For instance, hourly labor rates used to estimate base and depot labor costs will vary markedly, depending on the extent to which the direct labor cost is burdened by applying appropriate overhead charges. Many studies have omitted significant portions of the direct labor-hour cost burden. Another difficulty lies in assuming that cross-sectional operating and support costs are average costs sustained over the entire life cycle. The cross-section is likely to have been taken either during the steady state of a mature engine or during its immature dynamic state; since neither state is "average," a cross-section can seriously distort the estimate either up or down.

Previous studies have estimated engine ownership costs in a range of $20 to $200 per engine flying hour. Recent data obtained for this study indicate that costs can be several times higher (even after adjusting for inflation) for the newer, high-technology engines for comparable mission objectives. It is possible that some previous cost figures were valid for earlier weapon systems at specific points in time, but current systems are tending toward considerably higher average operating and support costs, and future systems threaten to be even more costly if no actions are taken to change the direction of this trend. Relying on older engine steady-state costs to directly reflect new engine average costs over a 15-year timespan can seriously underestimate future costs.

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[3] Studies by ARINC, LMI, JLC Panel, NASA, GAO, SAB, and most recently, PMR/HQUSAF, present some data but no cost-estimating methodology. The PMR study provides brief summaries of most of the other major studies. (See Refs. 2-8.)

OUTLINE OF THE STUDY

This study examines the magnitudes, proportions, and trends of costs for acquiring and owning a new aircraft turbine engine and highlights the parameters driving these costs for the benefits sought. It provides an overall life-cycle methodology that incorporates the effect of state-of-the-art advances required for new engines. Chapter 2 discusses the objectives, definitions, and data requirements for life-cycle analysis. Chapter 3 presents the results of the life-cycle analysis for military engines. Chapter 4 discusses applicable commercial experience. Conclusions and recommendations are presented in Chap. 5.

Chapter 2

LIFE-CYCLE ANALYSIS

The life-cycle analysis of a new weapon system must be based on an understanding of all phases of the life-cycle process, both separately and as they interact. They include concept formulation, validation, development, procurement, deployment, operational use, and disposal. The life-cycle process extends over two to three decades, depending upon the quality originally sought and the quality obtained, the length of time spent in each phase, and the importance of the system in the inventory. The creation of a weapon system involves many organizations within the Government, military service, and private industry. While life-cycle analysis must be sensitive to institutional practices, the central concern of this study is to develop a methodology that can be applied to benefit/cost tradeoffs.

DEFINITIONS AND QUANTITATIVE MEASUREMENT OF BENEFITS AND COSTS

It is often extremely difficult to evaluate quantitatively the benefits to be gained from a new weapon system. For example, the new system may incorporate a technical characteristic that appears to provide a marginal improvement at best over a previous system, but in reality creates a significant combat advantage— but how is that advantage to be measured? In the commercial arena, the bottom line is profit earned for the service provided (where safety is one implied part of service), but it is far from easy to assign a dollar-equivalent to the benefits a weapon system produces in a wartime environment. In attempting benefit and cost assessments for engines, it must also be recognized that analysis at the subsystem level must ultimately be related back to the system; engine output must be measured in terms of its contribution to the weapon system. The true measures are the engine's impact on weapon-system availability and utilization, mission reliability, effectiveness, mobility, and inventory life. Such measures are beyond the scope of this study, which confines its measure of output to the subsystem level. It is the task of the weapon-systems planner to transform the output measures dealt with in this study into the ultimate value of the system; the methodology presented here should enable him to do so with more confidence than has heretofore been possible.

DEFINING BENEFIT MEASURES FOR AIRCRAFT TURBINE ENGINES

The aircraft turbine engine has been characterized as one of the highly significant inventions of the twentieth century. Certainly, no one can deny the tremendous importance of the changes its military and commercial applications have wrought on our history and the way we live. But in this era everything comes with a price-tag. It has been said, somewhat wrily, that the only trouble with a turbine engine is that it weighs something, it gulps fuel, it takes up space, it creates drag, and it breaks now and then. Like all other inventions, it has its benefits, and it has its costs.

Benefit measures for an engine hinge on its design, how it is used, and how it affects weapon-system quality.

Quality is an extremely complex measure that defies absolute quantification in a military context. For an engine, it embraces the sum of the characteristics it is to contribute to a new weapon system (performance, durability, reliability, maintainability, safety), just as life-cycle cost is the sum of all cost elements. However, military quality is partly a subjective matter, more difficult to assess than cost. How much is an extra 50 miles per hour worth to a fighter aircraft? What is it worth to have the aircraft available more frequently? In the weapon system context, it is possible—and necessary—to arrive at rational dollar figures for the answers, but subjective judgment will always enter the calculations.

In a life-cycle analysis, we seek to clarify, at least in part, the tradeoffs among product quality, schedule, and total cost. When one characteristic of an engine is changed, other characteristics are affected. *Since quality is a combination of many things, it is not certain that an improvement in one characteristic of quality necessarily leads to an overall improvement in quality for the end use desired.* For instance, if performance is increased to the detriment of reliability, it is not clear that overall quality is improved. In this study, quality is considered closely synonymous with performance in a military context, and engine performance characteristics are related to the state of the art to assess their schedule and cost impacts in selecting a new engine.

For military systems, quality has primarily meant performance, with other characteristics considered secondary. The goal commonly has been to obtain thrust at a minimum fuel consumption, weight, and installed volume, but other characteristics should be considered. (Commercial practice emphasizes safety, reliability, and cost.) Durability and reliability are so closely related that they are somewhat difficult to distinguish; but durability can be related to design life, the engine's continuing ability to perform the mission in the aircraft during its inventory lifetime. This may entail consideration of several system output measures: flying hours, sorties, takeoffs and landings, engine cycles (throttle movement), and calendar time. Reliability can be expressed as the engine's ability to be ready to go on any given mission and to perform it successfully. Measures of interest are engine removal rates, mission aborts, and time between scheduled base maintenance and depot repair visits. Maintainability is the ease with which the aircraft/engine combination can be maintained in the field. Safety can include design features that may appear to detract from performance—for example, designing engine casings so blades cannot go through them if they separate from the rotor. Such a feature increases engine weight but reduces the chance of substantial airframe damage. Environment impacts include noise and smoke, which can be reduced at some penalty to engine performance.

The most widely used output measure of ownership cost for a given engine is *cost per engine flying hour.* In the future, however, other measures may become more relevant. With the advent of the high cost of fuel, flying training may be accomplished in fewer flying hours. But pilots can make fuller use of these flying hours so as not to cut down on critical portions of their training. Thus, in the future, flying hours may decrease, but not the number of sorties, takeoffs and landings, and engine cycles; if so, cost per flying hour may not be an appropriate measure. The cost of maintaining the engine inventory may not decrease even though there is a decrease in flying hours and fuel cost. This is especially true if maintenance is staffed to handle peak workloads in wartime. Another measure is calendar time. The longer an engine is out in the field without major depot rework, the more opportunity it has to undergo corrosive and secondary damage. When it does finally return to the depot, the damage may be more extensive than might be expected on the basis of flying hours alone.

Although this study will primarily use *engine performance* characteristics to relate to state-of-the-art and life-cycle costs, and the *engine flying hour* as an output measure for ownership costs, future data collection efforts should encompass other benefit measures—notably, sorties, takeoffs and landings, engine throttle excursions, and calendar time.

DEFINING LIFE-CYCLE COST ELEMENTS[1]

The life-cycle cost of an aircraft turbine engine is the sum of all elements of acquisition and ownership costs. To enable effective tradeoff decisions, detailed definitions of those elements are necessary, particularly in terms of what belongs under acquisition cost and what belongs under ownership cost. Table 2.1 lists those elements as they are used in this study. There are three columns in the table: (1) engine acquisition costs, comprising the RDT&E and procurement portions of the acquisition phase involving design, development, test, manufacture, and delivery to the field; (2) engine ownership costs, comprising operating and support maintenance costs for all base and depot activities; and (3) weapon-system-related costs for fuel and for attrition due to accidents and catastrophic failures.

Certain cost elements appear under both "acquisition" and "ownership" as, for instance, ECP/mod/retrofit costs. In one situation, they can be in the "acquisition" column because they are associated with enhancement of performance or a change in requirement that should be attributed to acquisition. In another situation, they can be associated with changes for correction of a deficiency and improvement of reliability and thus are attributable to ownership. Other costs appearing in both columns include AGE (common and peculiar), transportation, management, and training. These cost elements are not usually large in either acquisition or ownership (on-the-job training is significant, but difficult to separate from all other maintenance labor costs at the base or depot; also, initial recruitment training is not considered here). Facilities are usually a one-time expenditure and vary widely from program to program. They are included in the definition, but will not be considered further in this study. With the increasing complexity of new weapon systems, peculiar support equipment may become increasingly costly, particularly if it is considered to include software design and development as well as hardware, and if simulators and diagnostic systems are regarded as support equipment. This

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[1] In this study, all costs are expressed in constant dollars. Discounting may change some of the findings presented in Chap. 3, depending on the distribution of cost outlays over the time horizon of interest and the discount rate assumed.

Table 2.1

CLASSIFICATION OF LIFE-CYCLE COSTS

Cost Element	Acquisition	Ownership	Weapon-System-Related
RDT&E	X		
Flight test	X		
Tooling	X		
Proc. of install engine	X		
CIP		X	
Spare engine		X	
Spare parts (base/depot)		X	
Depot labor		X	
Base labor		X	
ECPs—mod/retro.	X	X	
AGE (peculiar/common)	X	X	
Transportation	X	X	
Management	X	X	
Facilities	X	X	
Training	X	X	
Engine attrition			X
Fuel			X

should be considered in future systems, particularly if engine health monitoring becomes an increasingly important factor in the design of new engines.

Engine attrition and fuel are classified as weapon-system-related because these cost elements depend primarily on the design and use of the particular weapon system. (Fuel consumption is a function not only of engine design but also of mission use; attrition rates depend on single-engine versus multi-engine application as well as other features.)

AIRCRAFT TURBINE ENGINE DATA[2]

Researchers attempting a life-cycle study of a weapon system constantly run up against the same obstacle: obtaining all the relevant data required. The problem is much like trying to put together a jigsaw puzzle when some of the pieces are missing and other pieces seem to have wandered in from another similar puzzle. Not only must the researcher comb through a large number of data systems, but there is the additional problem of inconsistency of data sources—two different data systems not agreeing when both supposedly use the same data from the same basic source.

The data most readily available for ownership cost-estimating in this study have been aggregated, heterogeneous, and cross-sectional, that is, gross, weapon-system-level or engine-family cost totals for only a few fiscal years and sometimes inconsistently defined across those years. A sound life-cycle analysis requires disaggregated, homogeneous, longitudinal data, cost data broken down below weapon system level, into consistently defined categories, and available over a considerable period of time, preferably at least ten years. In general, Air Force practice is to save costs for about three to four years.[3]

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[2] This is perhaps going to be changed in the near future with several data systems forthcoming at OSD and Hq USAF that may save costs over a long period of time. VAMOSC (Visibility and Management of Operating and Support Costs, OSD I&L) and OSCR (Operating and Support Cost Reporting, AFAC) are now being implemented. These systems could eventually also provide the kind of data needed at the subsystem component level.

For engines, the contractor is the best source of RDT&E CEP and procurement data, since he is in the best position to break out the detailed cost elements for each portion of the costs associated with a particular contract, and he saves cost data for many years. These data are valuable to him for analyzing new engine programs, whereas the military services, because specific contracts may cover a multitude of items procured by a lump-sum cost, are hard pressed to attempt a detailed breakout of costs long after the fact. For instance, a given Air Force contract may include not only the procurement of whole engines, but some allotment to spare parts, management data, field support, and so forth.

The only source of all relevant ownership data is the using military service. It is critically important to obtain all relevant costs in a particular area. For instance, depot costs are a large expense for engines. The total depot cost includes not only overhaul of whole engines, but also repair of reparable parts for whole-engine overhaul, the cost of expendable parts, modifications, and the repair of components received directly from the field and returned to the field. Some of these costs have not been included in previous studies attempting to obtain total depot costs.

The operating base has similar data problems. This is one area in which specific weapon system costs are significantly lacking. To obtain cost elements at the base, for example, the Resource Management System (RMS) is useful for costs associated with specific base cost centers. This system will provide the cost associated with operating the engine shop. Several difficulties hamper the collection of engine-related base costs: The engine shop is not the only source of labor related to engines; costs associated with the engine shop involve fixing all of the engines on a base, not merely the engine type of interest; and costs are not separated by weapon system. The analyst therefore must exercise care in obtaining the correct costs properly allocated, or apply some estimation technique that includes allocation.

[3] See App. B. for additional backup material

CHAPTER 3

MILITARY AIRCRAFT TURBINE ENGINE LIFE-CYCLE ANALYSIS

This study has a twofold objective: to develop a methodology for assessing life-cycle benefits and costs for military aircraft turbine engines, and to apply that methodology to policy considerations in the development, procurement, and ownership of engines. This chapter focuses on the development of that methodology and presents applications of it. Development, procurement, and ownership are explored at the engine subsystem level. The chapter analyzes data available for each phase of the life cycle and develops models following the theoretical formulations of Chap. 2. To satisfy these objectives, the chapter examines engine benefits and costs in detail to reveal magnitudes and proportions of life-cycle cost and identify trends and important variables.

Toward those ends, this chapter:

- Presents a methodology for measuring military engine quality by relating desired performance characteristics to time, specifically to the 150-hour Model Qualification Test (MQT) date, to obtain a Time-of-Arrival (TOA) trend for engines[12];
- Reviews the application of this methodology to estimating development and procurement costs and trading off performance schedule cost in the military acquisition process[1]; and
- Considers this same approach for investigating and improving ownership cost-estimation; ownership and acquisition can then be combined into an overall life-cycle perspective.

With such a perspective, the early planner can have a new ability to answer questions about tradeoffs between benefits and acquisition and ownership costs during the conceptual phase. For instance, can the effect of pushing the state of the art be measured in terms of overall performance schedule cost implications? Will pushing the state of the art increase component improvement costs? Will engine overhaul in the depot cost more? Will it cost more to maintain a more complex engine in the field? The TOA approach is used below to address such questions.

TIME OF ARRIVAL—A PROXY FOR TECHNOLOGY

Because technology is not directly measurable, a substitute measure has been sought. Such a measure must be associated with real-life applications, for technology cannot be considered an end in inself. Technology trends may then be tracked by recording the values of the measure in different applications at different times. A previous Rand study related the date of an engine's successful MQT to certain technical advances that military users had sought over time[1]. Later work related this measure of state-of-the-art trending to engine acquisition costs[1]. This area will be discussed in more detail shortly. The present study uses the same approach to extend the analysis to the entire life cycle.

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[1] See Ref 12. Other studies of technology trending include Refs. 13, 14, and 15

The proxy used for state-of-the-art advance in this study is the time of arrival (TOA) of a particular set of aircraft turbine engine characteristics at the 150-hour MQT date. A multiple regression technique was used to obtain the equation that predicts the TOA of the 150-hour MQT; the variables were thrust, weight, turbine inlet temperature, specific fuel consumption, and a pressure term that is the product of the pressure ratio and the maximum dynamic pressure of the engine's operating envelope—all of them important performance measures. The initial efforts in obtaining a trend for military engines concentrated on performance since these measures were most readily available and the military process has been essentially performance-oriented. Many additional variables were examined but did not add significantly to the quality of the model.

The data base for the model consisted of 26 turbojet and turbofan engines spanning a 30-year time period of aircraft turbine engine history. Some of the technological highlights of this time period are shown in Table 3.1. Although sporadic surges of technological advance have recurred, the overall trend has been one of steady evolution.* Time can therefore be used as a proxy for evolutionary technology when evaluating performance-schedule-cost tradeoffs in the selection of a new engine.

The 26 engines associated with the data base are shown historically in Table 3.2; the detailed data appear in Table 3.3. The results of the TOA model are portrayed in Fig. 3.1, which presents the model graphically. The 26 TOAs are plotted by the number of quarters of years from an arbitrary origin, October 1942, when the first U.S. turbojet-powered aircraft flew. The equation is displayed in the figure.

The statistical qualities of the model are very good, as is shown by the R^2 and standard error; the F and t tests for the model and coefficients were also extremely significant. Perhaps most important, all the variables have entered into the relationship in a manner consonant with theoretical considerations and operational experience.

TOA is a function of the technological characteristics of turbine engines. The signs of the coefficients in the TOA equations are consistent with intuitive notions of what constitutes more technologically advanced achievement with time: positive coefficients on variables for which larger values are more difficult to achieve, and negative coefficients on variables for which smaller values are more difficult to achieve. For example, as technology advances one would expect both pressure and turbine temperature to increase, and they have positive coefficients in the equation. One would expect weight and specific fuel consumption to decrease, and both have negative coefficients. The positive coefficient for thrust indicates that, on the average, the physical size of engines has grown over the 30-year history. Engines have considerably larger thrust today than they had 20 to 30 years ago. Figure 3.1 plots the Time of Arrival, TOA26, on the ordinate against the actual time of arrival on the abscissa for the 26 data points. The 45-degree line can then be visualized as a measure of the state of the art. An engine calculated to arrive on a certain date that does indeed arrive on that date falls on the 45-degree line. Data points falling above the 45-degree line represent advanced engines in the sense that they were calculat

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* For more discussion, see Ref. 12, pp. 11-19.

Table 3.1

SYNOPSIS OF AIRCRAFT TURBINE ENGINE DEVELOPMENTS

Early 1940s (WW II)	Late 1940s	Early 1950s (Korean War)	Late 1950s	Early 1960s	Late 1960s (Vietnam)	Early 1970s
			Engine Types			
Turbojet	Turbojet	Turbojet, turboprop/ turboshaft	Turbojet, turboprop/ turboshaft	Turbojet, turboprop/ turboshaft, turbofan	Turbojet turboprop/ turboshaft, turbofan	Turbojet, turboprop/ turboshaft, turbofan
			Trends in Engineering Development			
Increased thrust Centrifugal to axial compressor Single-design point mission Limited use of high-temperature steels; primarily conventional steels	Augmentation Two-position nozzle Stainless steel, aluminum, conventional steel Higher pressure ratio, dual rotor	High pressure ratio, variable stators Titanium begins to replace aluminum Sustained supersonic flight Small helicopter engines Reliability/ durability Moderately higher turbine temperature	Cooled turbine Mach 3 Small lightweight engines Commercial turbojet Subsonic turbofan Titanium and superalloy material improvements Transonic compressor	Supersonic turbofan Multidesign point mission Superalloy materials Lightweight design Component improvements Commercial turbofan	High-bypass turbofan (military and commercial) High-temperature turbine Cooling techniques 3-spool rotor Compatibility/ integration Increasing sophistication of development Commercial technology and requirements becoming as advanced as military	High thrust/weight High component performance High-temperature materials Cooling techniques Composite materials
			Companies			
General Electric Westinghouse	Allison Boeing Curtiss Wright Fairchild General Electric Pratt & Whitney Westinghouse	Allison Boeing Continental Curtiss Wright Fairchild General Electric Lycoming Pratt & Whitney Westinghouse	Allison Boeing Continental Curtiss Wright Fairchild General Electric Lycoming Pratt & Whitney	Allison Boeing Continental Curtiss Wright Garrett General Electric Lycoming Pratt & Whitney	Allison Continental Garrett General Electric Lycoming Pratt & Whitney	Allison Continental Garrett General Electric Lycoming Pratt & Whitney

Table 3.2

DATES OF DEVELOPMENT INITIATION FOR THE AIRCRAFT TURBINE ENGINE DATA BASE

Early 1940s	Late 1940s	Early 1950s	Late 1950s	Early 1960s	Late 1960s
J30 W	J40 W	J52 PW	J58 PW		TF34 GE
J31 GE	J42 PW	J65 CW	J60 PW		TF39 GE
J33 GE/A	J46 W	J69 C	J85 GE		TF41 A
J34 W	J47 GE	J75 PW	TF30 PW		
J35 GE/A	J48 PW	J79 GE	TF33 PW		
	J57 PW				
	J71 A				
	J73 GE				

NOTE: W = Westinghouse; GE = General Electric; A = Allison; PW = Pratt & Whitney; C = Continental; CW = Curtiss Wright.

Table 3.3

TECHNICAL DATA FOR U.S. MILITARY AIRCRAFT TURBINE ENGINES

Engine	Turbine Inlet Temp. (°R)	Thrust Max. (lb)	Weight (lb)	Pressure Term (lb/ft^2)	Specific Fuel Consumption (lb/hr/lb)	Mach No.	Max. Dia. (in.)	Length (in.)	MQT (qtr)
J30	1830	1560	686	1575	1.17	0.9	19.0	94	17
J31	1930	1600	850	1710	1.25	0.9	41.5	72	11
J33	1960	3825	1875	3400	1.22	1.0	50.5	103	19
J34	1895	3250	1200	3400	1.06	1.0	27.0	120	27
J35	2010	4000	2300	3400	1.08	1.0	40.0	168	21
J40	1985	10900	3580	5750	1.08	1.8	41.0	287	45
J42	1825	5000	1729	3640	1.25	1.0	49.5	103	25
J46	1985	6100	1863	6625	1.01	1.8	29.0	192	44
J47	2060	4850	2475	5375	1.10	1.0	37.0	144	26
J48	2030	6250	2040	4880	1.14	1.0	50.0	107	33
J52	2060	8500	2050	12840	0.82	1.8	31.5	150	74
J57	2060	10000	4160	11400	0.80	1.4	41.0	158	41
J58	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	87
J60	2060	3000	460	10360	0.96	1.0	24.0	80	71
J65	2030	7220	2815	8500	0.92	1.8	38.0	127	46
J69	1985	920	333	3400	1.12	1.0	22.0	44	56
J71	2160	9570	4090	11000	0.88	1.5	40.0	195	47
J73	2060	8920	3825	8750	0.92	1.9	37.0	147	49
J75	2060	23500	5950	16724	0.80	2.0	43.0	259	59
J79	2160	15000	3225	18056	0.87	2.0	37.5	208	57
J85	2100	3850	570	10360	1.03	2.0	20.0	109	74
TF30	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	92
TF33	2060	17000	3900	19240	0.52	1.0	53.0	136	71
TF34	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	120
TF39	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	109
TF41	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	107

[a] Deleted for security or proprietary reasons.

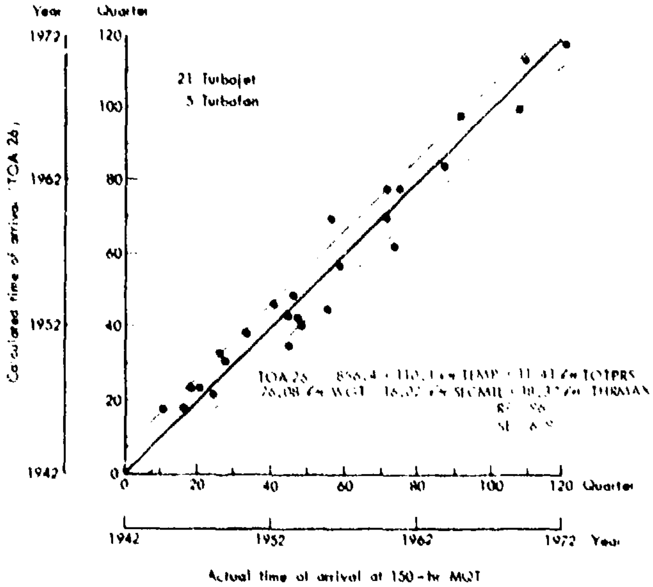

Fig. 3.1—Military growth engine time of arrival

ed to arrive on a certain date and they arrived earlier. They were ahead of schedule or were advanced. Conversely, engines below the 45-degree line would be considered conservative. The standard error is shown by the dashed lines.

Many engines have both afterburning and non-afterburning models. The data utilized to obtain the TOA model represent "primary" engines in the sense that each is used only once, according to its first MQT; no product improvement models are included in the figure. The model that first passed an MQT is the one selected for use in the TOA equation. If the MQT engine had no afterburner but subsequent models did, as in the case of the J57, the non-afterburning version was used. Similarly, if the MQT engine had an afterburner and subsequent models did not—the TF30, for example—the afterburning version was used.

The model and its statistical properties are summarized in Table 3.4; the table also includes an example of the application of the equation to the J79 engine. The J79 represents approximately the middle of the 30-year trend. The contribution of each variable to the calculation is shown. The result indicates that the J79 was significantly advanced when it passed its MQT. Also shown are elasticities for the variables (or the effect that a percentage change in the independent variable will have on a percentage change of the dependent variable). The predominant variable in the calculation is turbine inlet temperature, which is extremely important in turbine engine technology. Higher temperatures allow the engine designer much more flexibility to trade off design and performance characteristics in terms of thrust, SFC, and physical size of the engine, which affects weight. The advance in temperature also implies that materials and design techniques such as combustor and turbine cooling are improving, so that the design can handle the higher temperature. The other variables, while highly significant statistically and important in an engine design, contribute less in the TOA equation. SFC appears to have the least impact, although as SFC continues to decrease, its effect could become significantly larger.

Table 3.4

AIRCRAFT TURBINE ENGINE TIME-OF-ARRIVAL (TOA) EQUATION

$$\mathrm{TOA26} = -856.4 + \underset{(5.8)}{110.10\,\ln \mathrm{TEMP}} + \underset{(3.1)}{11.41\,\ln \mathrm{TOTPRS}} - \underset{(5.1)}{26.08\,\ln \mathrm{WGT}}$$

$$- \underset{(2.8)}{16.02\,\ln \mathrm{SFCMIL}} + \underset{(2.8)}{18.37\,\ln \mathrm{THRMAX}}$$

$R^2 = 0.96$
SE = [illegible]
$F = 92\ (5,20)$

Example: J79 Engine

Variable	Value	Calculation[a]	Elasticity
Constant	−856.4	−856.4	—
TEMP	2160	+845.3	+1.5
TOTPRS	18056	+111.8	+0.2
WGT	3225	−210.7	−0.4
SFC	.87	+2.2	−0.2
THRMAX	15000	+176.6	+0.3
TOA26		68.8	
MQTQTR		57	

[a] Equation coefficient multiplied by value of variable (in appropriate form); e.g., for TEMP: 110.10 ln 2160 = + 845.3.

Of particular interest during early planning at the conceptual phase would be an engine falling outside the standard error on the high side, namely, a significantly advanced engine in terms of the data base. Some data points do fall outside the standard error on the high side, such as the J79 example shown. An advanced engine can be achieved, then, but the model suggests that it be more difficult than achieving an average engine. It is to be expected that an advanced engine has a higher exposure to performance shortfall and schedule slip and, as will be shown subsequently, will tend to be more expensive to develop and procure. There is also some qualitative evidence (but as yet insufficient quantitative data) that such an engine may be more susceptible to "teething" problems when introduced into operational service. If an engine fell within the standard error where two-thirds of the data would be expected to fall, it would be difficult to say whether it was significantly advanced or conservative. An engine outside the standard error on the lower side would tend to be significantly conservative for the time that it did arrive. But this is not to say that an existing engine (as shown in the figure) on the conservative side was expected to arrive on that date. It may have slipped from a schedule that was expected to produce an advanced engine or an engine within the state of the art. (Planning information concerning when an engine was supposed to pass its MQT was not available for most older engines.) In fact, no engine currently in the USAF inventory has started out to be deliberately conservative. This may have implications for the overall trend today of designing to cost. Most military engines in the inventory to date have been primarily performance-oriented, with durability, reliability, maintainability, and cost considerations second. It would be an innovation to design an engine to cost, with deliberately conservative performance characteristics.

As will be shown in the cost analysis to follow, the development of engines beyond the MQT after they enter operational service is often more costly than the entire development program up to the MQT. As an illustration of the application of the TOA technique, an analysis was made of the additional technological growth of 13 engines after their original MQT. It would be expected intuitively that the growth version of an engine already in production would have limited design flexibility, because many of its features are constrained by the existing hardware and production capabilities. Hence, technology improvement for updated engines should be slower than that for new engines. This expectation is borne out by Fig. 3.2, portraying post-MQT technology growth for 13 engines. The left-hand point of each pair of points is the TOA of the original MQT engine, and the right-hand point is the TOA of the most improved version. The connecting line indicates the rate of technological growth for each engine relative to the state of the art. All engines showed growth curves of less than 45 degrees. A Rand study [16] has investigated, to a limited degree, the type, amount, and cost of technological change through growth models of turbine engines.

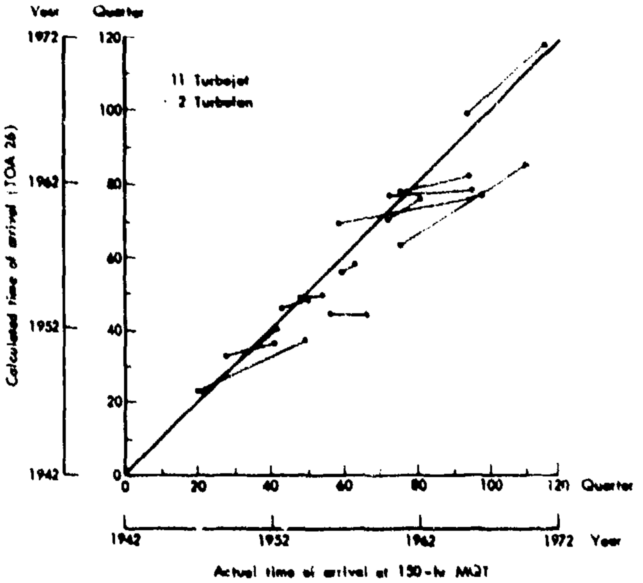

Fig. 3.2—Military turbine engine time of arrival

Application of TOA

This TOA approach will be used to estimate, first, development and production costs during acquisition, and later ownership costs, using two time measures along with other parameters that are expected to be significant in the cost-estimating relationships (CERs). Figure 3.3 presents these terms. TOA is the time-of-arrival level for a particular engine calculated from the equation and measured from the origin. ΔTOA is the difference between the calculated TOA when an engine is expected to pass its MQT and the actual or scheduled MQT measured from the 45-degree trend line. Both of these terms will be used in attempting to improve the CERs for engine acquisition.

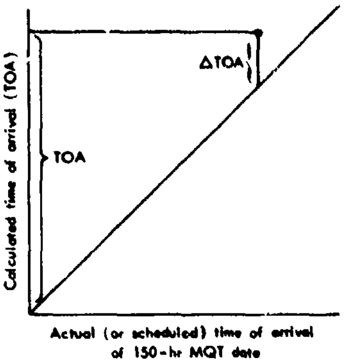
Calculated time of arrival (TOA)
ΔTOA
TOA
Actual (or scheduled) time of arrival of 150-hr MQT date

Fig. 3.3—Relationship between predicted time of arrival and deviation from the trend

It must be emphasized that the TOA methodology does not directly measure a trend of technology, per se, but a time trend of the parameters associated with the successful application of technology: the development, production, and use of products to meet user demand. The methodology enables the user to discriminate between performance measures that have unequal value for him. The following assumptions and limitations apply to this methodology:

1. The model implies steady, evolutionary development. Progress made in a time interval in the 1950s is equal, relatively, to progress made in a similar time interval in the 1970s.
2. There is continuing support of the technology base. The exploratory and advanced development programs and the IR&D effort are continuous and ongoing. Operational experience and component improvements in existing hardware also provide information.
3. In predicting new engines, it is assumed that the future will behave similarly to the past in the sense that the acquisition process will not vary greatly, and that the values applied by the user will be fairly similar. Thus, design-to-cost, as opposed to the current military philosophy of design-to-performance, must still be evaluated cautiously in a military context. However, combining military and commercial experience may yield new insights concerning the value of characteristics other than performance in attempting to obtain an overall trend of quality in an engine.
4. In predicting the future, it is important that the variables associated with new products be a reasonable extension of the available data base vari-

ables. Near-term future predictions are therefore likely to be more valid than far-term predictions. The variables must certainly be internally consistent with regard to thermodynamic cycle characteristics for the design being evaluated. A large increase in a single variable is thus precluded from consideration for a new engine program. Steady improvement in all variables has been the experience.

5. The data base is for all industry products, and the model reflects average industry experience. Thus, the model may not totally reflect a particular manufacturer, since there are leaders and followers in any industrial and technological area.

There has been continual pressure to advance technology during the 30-year period covered by the engine data used in this study, and continuous progress has been achieved. These observations and supporting analysis [1,12] indicate that the MQT date generally orders the level of technology of engines, and that TOA provides an *ordinal* prediction of an engine's level of technology. In this technological sense, the measure is not cardinal because the differences cannot be directly compared.

The technology and cost models are of interest to planners and cost estimators whether TOA is a cardinal or ordinal measure. Planners will use any available tool to obtain the "best" solution for the decisions that confront them. Interest has been focused on this issue because a cardinal measure of technology is intrinsically desirable: Such a measure would provide a sounder theoretical basis for cost estimation than have the more "conventional" approaches used in the past. Indeed, some past efforts have been more concerned with variables that best explain the data, with insufficient regard for their theoretical appeal. The TOA measure seems to be a more objective measure of technological state-of-the-art advance than has been previously obtained and used in cost-estimating relationships, but *TOA is not a cardinal measure of technology*. It is a proxy for technology, and it does attempt to relate technology to time through user values of products obtained, and *time is therefore used in a cardinal sense* in the cost-estimating models that follow.

Data Analysis

Data were obtained and analyzed prior to development of CERs. Development costs for 14 military turbojet and turbofan engine programs and procurement costs for 18 such programs were obtained and used to generate acquisition cost models utilizing TOA and ΔTOA. Reference 1 contains a detailed discussion of the data and their treatment. These data were obtained almost exclusively from contractors. Ownership data, on the other hand (except for CIP), were obtained mainly from Air Force organizations. These data were severely limited as to quality and time-span, limiting the model results that could be obtained in the ownership area. Interesting insights were obtained concerning magnitudes and proportions of costs for particular ownership expenses, and some model results are useful as crude estimates of costs. Ownership cost models will be addressed following discussion of the acquisition cost models.

Relating Time of Arrival to Acquisition Costs

The methodology involving a time of arrival for relating performance to development schedules has been incorporated into cost-estimating relationships (CERs) for the engine acquisition process. These CERs were developed for U.S. military engine development and procurement costs.[3] Homogeneous, disaggregated cost data were available from the engine contractors, spanning a 25-year period in some cases. Without this type of data, meaningful results could not have been obtained. The approach employed here was to investigate variables considered important in the development and procurement phases of a new engine. The variables included measures of the quality of the product, the development time involved, the "technology" (time of arrival) embodied in the product, and how much additional "technology" the program apparently required. Results of these CERs are shown in Tables 3.5 and 3.6 for development to MQT and for the thousandth production unit selling price. Example calculations and elasticities for the J79 engine are also presented.

Table 3.5

COST MODEL FOR DEVELOPMENT TO MQT
(In millions of 1975 dollars)

$$\begin{aligned} \ln \mathrm{DMQTC} = -1.3098 &+ \underset{(7.6)}{0.08538\ \mathrm{DEVTIME}} + \underset{(7.1)}{0.49630 \ln \mathrm{THRMAX}} \\ &+ \underset{(4.9)}{0.04099\ \Delta\mathrm{TOA26}} + \underset{(2.3)}{0.41363 \ln \mathrm{MACH}} \end{aligned}$$

$R^2 = 0.961$
$SE = 0.182$
$F = 55.7\ (4,9)$

Example: J79 Engine

Variable	Value	Calculation	Elasticity
Constant	-1.3098	-1.3098	–
DEVTIME	18	+1.53684	+1.6
THRMAX	15000	+4.77232	+0.5
ΔTOA26	11.8	+0.48368	+0.5
MACH	2.0	+0.28674	+0.4
ln DMQTC		5.76978	
DMQTC		320.0	
Actual DMQTC		32[illegible].0	

In the models studied, the variables have entered with coefficients that satisfy theoretical considerations and/or actual experience. The signs of the coefficients are in the right direction in terms of what an engine designer would expect concerning changes in these variables and the resultant effect of such changes on cost. In the development cost model, for instance, development time entered positively, indicating that the longer the program, the higher the cost. The implication here is that continuously higher-quality products entailing longer development times have been desired over the 30-year trend. It must be noted, however, that a mini-

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[3] For a more detailed discussion, see Ref. 1, pp. 20-49

Table 3.6

COST MODEL FOR THOUSANDTH PRODUCTION UNIT SELLING PRICE
(In millions of 1975 dollars)

$$\ln \text{KPUSP} = -8.2070 + \underset{(9.2)}{0.70532 \ln \text{THRMAX}} + \underset{(2.8)}{0.00674\ \text{TOA26}} + \underset{(2.6)}{0.45710 \ln \text{MACH}} + \underset{(2.4)}{0.01804\ \Delta\text{TOA26}}$$

$R^2 = 0.951$
SE = 0.215
F = 63.0 (4,13)

Example: **J79 Engine**

Variable	Value	Calculation	Elasticity
Constant	−8.2070	−8.2070	—
THRMAX	15000	6.78222	+0.7
TOA26	68.8	0.46371	+0.5
MACH	2.0	0.31684	+0.5
ΔTOA26	11.8	0.21287	+0.2
ln KPUSP		−0.43136	
KPUSP		0.650	
Actual KPUSP		0.631	

mum development time on the order of four to five years for a new engine program must be associated with this estimating relationship, since in the extreme this relationship could result in zero development cost at zero time. It takes some amount of time to develop a new engine, of course, however simple it may be; the model therefore must use some minimum development time. The coefficients of the other variables also accord with expectations. Thrust enters positively. The larger the engine, the higher the development cost. ΔTOA and Mach number enter positively; they relate to the state-of-the-art increment to be obtained (or additional time increment required beyond an "average" development—the program's technology "reach") and complexity of the engine due to the environment in which the engine has to operate.[4]

For J79 development costs, as shown in Table 3.5, the largest contributor is thrust, with development time second. In terms of elasticity, it appears that development time is the most significant for development cost. For the thousandth-unit production cost model (Table 3.6), the largest contributor again is thrust. It also has the highest elasticity for the J79 example shown. In both examples ΔTOA, although making a fairly small contribution to total costs, significantly increases development cost and production unit cost: by over 60 percent and over 20 percent, respectively. The development and production cost estimates obtained with this approach are very close to the actual data for the J79, as shown in Tables 3.5 and 3.6.

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[4] See, e.g., Ref. 17, where Mansfield characterizes elements of development as size and complexity (thrust and Mach No.), the magnitude of advance (ΔTOA), the stock of knowledge (TOA), and the development time (DEVTIME), all of which showed up in models obtained. (TOA is not highly significant in the military development cost model but was significant in a combined military and commercial model.)

To calculate the cost of procuring a quantity of engines, it is necessary to determine a progress curve slope for the particular engine program (or assume one on the basis of a particular manufacturer's experience) and then use a procedure for obtaining the total cost of the quantity desired, knowing a unit cost and slope.[6]

Tables 3.7 and 3.8 present models for progress slope and production quantity cost. Several variables had to be introduced in developing the models. One was a manufacturer's dummy, which was necessary to adjust for the significantly different accounting practices used by one of the manufacturers prior to 1971. Accounting practices must be understood so that all appropriate cost elements are accumulated and costs are on a comparable basis. Changing accounting practices require that a detailed cost trail be maintained as the years go by so that the equivalent cost elements can always be obtained from the data on an annual basis.

Table 3.7

CUMULATIVE AVERAGE PRODUCTION UNIT PROGRESS SLOPE[a]

$$\begin{array}{l} \text{Slope} = 0.85735 + \underset{(2.4)}{\text{MFRDUM}^{b}} - 0.53243\ \underset{(2.7)}{\text{KPRATE}} + 33.743\ \underset{(2.3)}{\text{MQTY}} \\ \qquad - 0.07170\ \underset{(2.1)}{\text{MVOLUME}} + 0.00106\ \underset{(1.8)}{\text{TOA26}} \end{array}$$

$R^2 = 0.789$
SE = 0.044
F = 9.0 (5,12)

[a] A manufacturer's estimated slope based on a particular engine program is the preferred alternative at present.

[b] Coefficients for MFRDUM are not shown because they do not apply to new engines. Significance levels are shown to indicate the importance of distinguishing between one particular manufacturer and the other companies historically.

The slope model, although quite interesting for the information it conveys, is not of the quality of the development and production models; it is included here for illustrative purposes only. It would have to be improved before it could be used extensively. For the time being, the wisest course would be to select a progress slope on the basis of a specific manufacturer's experience and specific program information.

As an alternative to using an assumed progress slope and the thousandth production unit selling price, a model of production quantity cost was examined. Several of the variables of interest were found to be significant in this model.

The model obtained for production quantity cost, as shown in Table 3.8, contains TOA26 and ΔTOA26 as well as the manufacturer's dummy resulting from differences in manufacturers' accounting practices. The most significant variables,

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[6] The procedure is well documented in the literature. See Ref. 18 for the seminal work at Rand in this field, and Ref. 1 for application to engines.

Table 3.8

CUMULATIVE PRODUCTION QUANTITY COST MODEL
(In millions of 1975 dollars)

$$\ln \text{PRQTYC} - 7.8504 + \underset{(45.0)}{.8697 \ln \text{QTY}} + \underset{(24.0)}{.82204 \ln \text{THRMAX}} + \underset{(6.0)}{\text{MFRDUM}}$$

$$+ \underset{(5.0)}{.0158\, \Delta\text{TOA26}} + \underset{(4.0)}{.34478 \ln \text{MACH}} + \underset{(2.4)}{.00277\, \text{TOA26}}$$

$R^2 = 0.97$
SE = 0.214
F = 501.7 (6,81)

Example: J79 Engine

Variable	Value	Calculation	Elasticity
Constant	-7.8504	-7.8504	—
QTY	13000	8.2384	+0.9
THRMAX	15000	7.9046	+0.8
ΔTOA26	11.8	0.2192	+0.2
MACH	2.0	0.2398	+0.3
TOA26	68.8	0.1906	+0.2
ln PRQTYC		8.9422	
PRQTYC		7648.1	
Average unit cost		0.588	

however, in terms of entry into the model, contribution to the calculation, and elasticity, are quantity and THRMAX. Certainly, quantity should be most significant in this type of model and THRMAX, again, is a measure of the physical size of the engine to be produced. The contribution of the manufacturer's dummy is zero for the GE engine. ΔTOA significantly increases the production quantity cost: about 25 percent for the hypothetical example shown.

In future research, the methodology could be expanded to encompass design objectives other than performance for the military. This will be explored further in Chap. 4, which discusses commercial experience in an effort to expand on the quality of the engine in areas concerning durability, reliability, maintainability, safety, and environmental impact. If all of the quality elements considered important for engines could be more fully understood, the possible tradeoffs in the acquisition process, and between acquisition and ownership, could be addressed, at least at the component level for aircraft turbine engines.

It should be emphasized again that, in all the work applying this approach to estimating the state of the art for the acquisition of military engines and for improving development and production cost estimates, not only were the CER models statistically improved by using this methodology, but all the variables of interest entered the models in a theoretically satisfying way. The approach may have benefit in planners' early attempts at broad tradeoffs among performance, schedule, and cost. It could be used to measure the risk that an engine will not achieve its MQT date, where risk includes the possibilities of performance shortfalls, schedule slip, and cost growth. This will be shown in the following example.

A HYPOTHETICAL EXAMPLE OF PERFORMANCE/SCHEDULE/COST TRADEOFFS IN THE ACQUISITION PROCESS[*]

An example of the application of the TOA methodology to the acquisition of a new engine is presented here. The engine is an afterburning turbofan engine for a new fighter aircraft. The data for this engine program were selected to represent an advanced engine that would fall outside the standard error on the high side in the TOA analysis—an engine significantly ahead of its time. Table 3.9 lists the performance variables, planned development schedule, and production quantity.

Figure 3.4 depicts several definitions for schedules of interest to our tradeoff analysis. The characteristics and schedule assumed for the new engine presented in the table will result in a data point outside the standard error on the high side, and thus in an engine advanced for the time it is being sought, but other alternatives are also possible.

Table 3.9

PERFORMANCE CHARACTERISTICS AND SCHEDULE FOR A HYPOTHETICAL NEW AFTERBURNING TURBOFAN ENGINE PROGRAM

Performance variables	
Maximum thrust (SLS), lb	24,000
Weight, lb	3,000
Turbine inlet temperature, °R	2,900
Specific fuel consumption, lb/hr/lb	0.70
Pressure term, lb/ft^2	72,000
Mach number	2.4
Planned development schedule and production quantity	
150-hr MQT date, quarters since 1942	124
Development time from start to MQT date, quarters	20
Quantity produced (including flight test and spares)	1,935
Manufacturer progress slope assumed	0.90

The first development-schedule possibility of interest in the figure is the *On Time* schedule: The engine is desired at an early date and is obtained on that date, with the ΔTOA shown and the five-year development schedule. In the second possibility shown, the development time slips almost to the *On Trend* line: The engine was not ready on schedule. (The triangle formed by the ΔTOA, the development time extension, and the 45-degree line represents the area of tradeoff in terms of performance and schedule, and these two parameters affect the likely acquisition cost of the engine as reflected in the CERs. This triangle represents a performance/schedule/cost tradeoff area.) A third approach to the development schedule is to "schedule" the *desired* engine near the trend line (the 45-degree trend line) and assume an average development time. Currently, an average engine takes about five years to develop. Thus, for this example, one would wait about a year and a half before starting the average engine program in order to obtain the stipulated performance level close to the 45-degree line; the resulting program would, of course, be able to use the extra time to incorporate the technology accumulated

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[*] This example is patterned after one presented in Ref. 19, pp. 11-14.

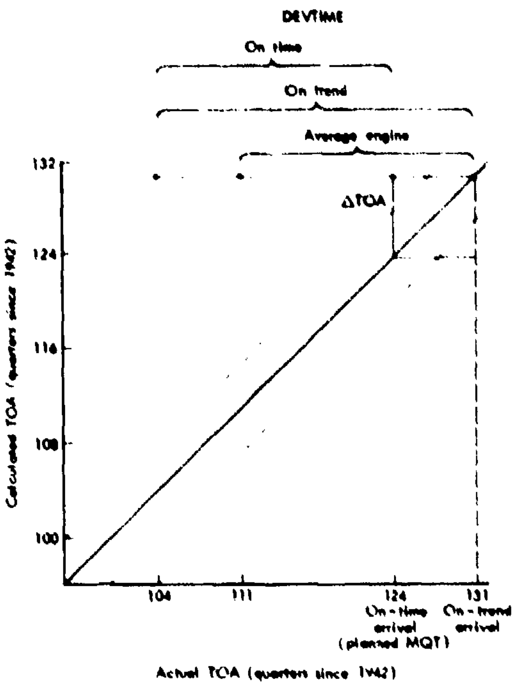

Fig. 3.4—Schedule definitions for tradeoff and risk analysis

during that period, assuming technology moves ahead in a steady evolutionary manner through continuous support of the technology base.

The acquisition costs for 1) the advanced program obtained on time, 2) the advanced program with a schedule slip, and 3) the average program scheduled to be obtained near the trend are compared in Table 3.10. For the advanced program achieved on time as planned (col. 1), the development cost is estimated to be $428 million. The thousandth unit production cost is $1.38 million, with a progress slope of 0.90, resulting in a cumulative production cost of $2.841 billion and a total acquisition cost of $3.269 billion. Had this program slipped to about the trend line (col. 2), the development cost would have increased to $559 million. The production unit cost would *not* have changed, because the slip would not have been known until the program reached the point where it was supposed to pass the 150-hour MQT and then had difficulty making it. Thus, this production cost represents an engine design configuration set some time previously, and the same production dollar cost applies in both of these situations. The total acquisition cost comes to $3.400 billion. The average program on trend (col. 3), with the five-year development time planned, turns out to have a lower development cost, $335 million, a lower thousandth-unit cost, $1.24 million (because the developer waits and uses that time to incorporate the technology learned during the interim period), and a lower cumulative production cost, $2.885 billion.[7] The total acquisition cost for the average

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[7] Implicit in this analysis is the assumption already noted that technology-base programs are proceeding steadily and that improvements are continuously available over time for both development and production phases of the program.

Table 3.10

ACQUISITION COSTS FOR THREE POSSIBLE OUTCOMES OF THE
HYPOTHETICAL ENGINE PROGRAM
(In millions of 1975 dollars)

TOA, Time, and Cost Elements	(1) Advanced Program On Time	(2) Advanced Program Near Trend (6 Quarter Slip)	(3) Average Program On Trend
TOA26, quarters	131.2	131.2	131.2
MQT date, quarters	124.0	130.0	130.0
ΔTOA26, quarters	7.2	1.2	1.2
Development time, quarters	20.0	26.0	20.0
Development cost	$428	$559	$335
Production cost			
1000th unit	$1.38	$1.38	$1.24
Slope	0.90	0.90	0.90
Cumulative production cost	$2841	$2841	$2550
Total acquisition cost	$3269	$3400	$2885

program is about $400 million less than that of the advanced program obtained on time. The advanced program with a schedule slippage is the most expensive, of course.

This example focuses on the engine subsystem. Not mentioned here, but certainly of great concern to a weapon system planner, is what effect the engine has on the entire weapon system; an engine schedule slip implies significant cost growth and schedule slip of the entire weapon system—and a new engine is usually the pacing development subsystem in a new weapon system. On the other hand, an advanced engine may contribute considerably to reducing the life-cycle cost of the entire weapon system through a reduction in airframe weight and fuel consumption.

OWNERSHIP OF AIRCRAFT TURBINE ENGINES

The ownership of an aircraft turbine engine encompasses all of the operating and support costs related to operating and maintaining the engine by and for the benefit of the user. In this study, "benefits" are expressed primarily in terms of the cumulative engine flying hours for the engine quality obtained for a specific weapon system. Ownership costs associated with those benefits include component improvement programs (CIPs) related to continuing the development of an engine after its MQT; the spare engines required to support the installed inventory by keeping the pipeline filled during base and depot repair; the engine labor and parts at the operating base to keep the fleet flying; depot labor and parts for maintenance support to restore engines and reparable parts to flying status; all modification labor and parts associated with parts changes during the course of an engine's maturation and steady-state experience; ground support equipment and tooling to support the engine in the field and at the depot; transportation costs for parts and engines shipped between bases and depots; management costs related to base and depot; facilities; and training. Engine attrition and fuel consumed are also extremely important, but in this study are considered weapon-system-related and must be identified separately. They are certainly ownership costs that should be considered in any tradeoffs. Base labor and parts, depot labor and parts, modifications, ground support equipment, transportation, management, and training costs are considered under the broader heading of engine maintenance and support costs. This study concentrates on CIPs, base and depot maintenance and support, and spare engines as the largest contributors to engine ownership costs. Transportation and management costs are considered to be of secondary interest. Facilities are not included here because they are considered program-specific.

This study is primarily concerned with variable life-cycle costs. In an economic sense, all costs are considered variable in the long term. However, in considering a new weapon system five to ten years into the future, certain costs are considered fixed in this study. These costs are associated with owning and opening bases or depot facilities. Consequently, the variable portion of base operating support costs and depot operating costs are addressed. Costs have been obtained from various sources. Appendix B provides details on the data collected and analyzed.

Component Improvement Programs

A CIP for an aircraft turbine engine provides funds for continuing development and engineering support activities beyond the 150-hour MQT date. The intent is to improve the product by correcting deficiencies revealed in operational experience, improving reliability throughout operational use, reducing costs for parts and repairs, and allowing the engine, through sustained engineering, to age gracefully during its operational lifetime. The development to MQT is intended to provide a specific level of performance at a minimum acceptable level of endurance and reliability to the user. Engines are designed with certain parts life, but only through testing and use can this inherent durability be assessed and engine reliability be improved. It is said by engine designers that you design an engine to durability (life) specifications, but you test to reliability. At the MQT date, the engine is considered suitable for operational use and for full-scale production, but at this point in time it is by no means a fully developed product.

The CIP funds an engineering effort to correct deficiencies found through testing and operating the engine in the field, to improve the reliability of the hardware, and to devise new repair techniques to aid base and depot maintenance. The effort to correct deficiencies involves engine design changes, which are then tested to verify that parts have been improved. Perhaps the original parts were breaking or wearing to the extent that they had to be replaced more often than was considered normal or desirable, and the weapon system therefore had a lower capability than expected (because of downtime while engines were removed and replaced).

There is a distinction between service-revealed design deficiencies and low reliability. Low reliability in an engine may be tolerable so long as it does not threaten imminent catastrophic failure and does not cause a large loss in capability or excessive maintenance costs. By contrast, some design deficiencies threaten catastrophic failures and must be corrected immediately upon discovery. Meanwhile, the fleet must be grounded. That distinction must be kept in mind when one is considering a design change for a particular part.

CIP money is also used to reduce costs through improved parts design. Successful redesign can reduce spare parts costs and production-unit cost for new engines ordered, and reduce repair costs at the base and depot. CIP funds are also spent on evaluating new repair procedures for base and depot as the hardware ages.

Besides these activities, it was common practice before 1969 to use part of the CIP funds to enhance the performance of the engine or prepare it for a new application. This practice is no longer allowed. Today, any funding required for those purposes must be identified separately within the allowable budgetary category. Unfortunately for this analysis, then, pre-1969 CIP data are not sufficiently disaggregated to permit identification of the dollar amounts apportioned to the multiple objectives of CIPs. We should remark in passing, however, that the boundary line between parts improvement and performance enhancement is often hazy to begin with. Parts improvement can either improve engine durability/reliability at the same performance level, or improve performance at the same durability/reliability level. The past military preference has been for performance improvement—weapon systems can always use a little more performance.

In the present analysis, all CIP costs are included for all years and all sources. They include U.S. and overseas allowances against sales (for instance, J79 foreign sales also contribute a portion of the selling price to CIP funds). All CIP costs in turn are included in this study's analysis of total post-MQT development costs over the past quarter century.

CIP Costs

What has been the magnitude of this CIP activity and how does it relate to money spent for RDT&E? An analysis of eight major engine programs indicates that more money has been spent on CIP *after* MQT than was spent to get *to* MQT. The costs for RDT&E do not include engine-related costs associated with weapon-system flight testing. The CIP costs reported here do include performance enhancement and additional applications within specific engine programs so that the data are consistently defined. The eight major engine programs that were investigated were the J52, J57, J60, J75, J79, J85, TF30, and TF33.[8]

Figure 3.5 presents total development cost profiles over time for these engine programs, normalized to their cost and development time required to achieve MQT. As can be seen, large expenditures are made for a considerable time after MQT. In 1975 dollars, these eight engine programs required $1.9 billion to achieve MQT. They have required a total of $5 billion to date for total development, i.e., the combined MQT and CIP costs. These costs include the performance growth and application enhancement funds, which are substantial in any program. It would be useful in future analyses to attempt to separate the performance and application monies from those for correction of deficiencies and reliability improvements for data prior to 1969; a model might then be developed on the basis of the current definition of CIP.

For most new engines over a 15-year life cycle, CIP costs will probably be somewhere close to MQT costs, not including performance enhancement or new

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[8] The TF34, TF39, and TF41 were not considered in this analysis, because their introduction into operational service has been more recent. They have on the average considerably less than ten years of operational experience.

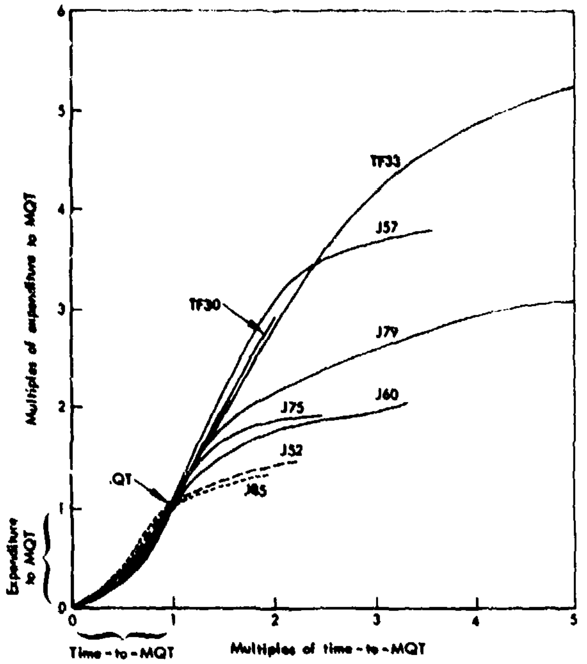

Fig. 3.5—Relative development costs before and after MQT for selected aircraft turbine engines (Ref. 1)

applications. These CIP activities definitely should be identified separately, and CIP considered a cost of ownership.

Cost Models for Total Development and Component Improvement Programs

For use in this study, contractors have supplied the detailed annual costs associated with individual engine CIPs. These costs were used to develop models relating the continuing CIP cost to engine parameters of interest, so as to obtain cost-estimating relationships (CERs).* Parameters expected to be significant or to shed light on CIP costs have been investigated. They include variables related to the physical size of the engine, the environment the engine is expected to operate in, some measure of the operating time span that the engine has been out in the field (related to its maturation), the quantity of the engine produced (which would indicate the size and significance of the program and thus its expected level of support and the importance of correcting engine problems), and the TOA and ΔTOA terms relating to user preference.

Models were examined both for total development cost (which includes the development cost to MQT plus all the continuing costs after MQT), and for only those continuing CIP costs after MQT. Table 3.11 presents the best model obtained for total development; Table 3.12 presents the best CIP model. For total development cost, the significant variables are the Mach number (the severity of the

* The data base used in this analysis is expanded from that in Ref. 1

Table 3.11

TOTAL DEVELOPMENT COST MODEL
(In millions of 1975 dollars)

$$\ln \text{TDC} = 0.97355 + \underset{(10.26)}{1.23809 \ln \text{MACH}} + \underset{(6.75)}{0.07345 \ln \text{QTY}}$$

$$+\ 0.40386 \ln \text{THRMAX} + \underset{(2.11)}{0.00918\ \Delta\text{TOA26}}$$

$R^2 = 0.941$
SE = 0.182
F = 114.8 (4,29)

Example: J79 Engine

Variable	Value	Calculation	Elasticity
Constant	0.97355	0.97355	—
MACH	2.2	0.97618	1.2
QTY	13000	0.69577	0.1
THRMAX	17900	3.95482	0.4
ΔTOA26	11.8	0.10832	0.1
ln TDC		6.70864	
TDC		$819	

NOTE: Thus, CIP = $819 - $320 = $499 million for the J79 example. The actual value at that point in the program was estimated to be about $600 million.

Table 3.12

COMPONENT IMPROVEMENT PROGRAM COST MODEL
(In millions of 1975 dollars)

$$\ln \text{CIP} = -2.79026 + \underset{(9.1)}{0.78862 \ln \text{THRMAX}} + \underset{(5.7)}{0.04312\ \Delta\text{TOA26}} + \underset{(2.5)}{0.00722\ \text{OPSPAN}}$$

$R^2 = 0.88$
SE = 0.29
F = 60.5 (3,22)

Example: J79 Engine

Variable	Value	Calculation	Elasticity
Constant	-2.79026	-2.79026	—
THRMAX	17900	7.72261	0.8
ΔTOA26	11.8	0.50882	0.5
OPSPAN	80	0.57760	0.6
ln CIP		6.01877	
CIP		$411	

operating environment), the quantity of engines produced, maximum thrust (the physical size of the engine), and ΔTOA (the increment of technological advance sought) as obtained from the TOA methodology. The results for this model are very good. (R^2, standard error, and F tests, as well as the individual t statistics for the coefficients in the equation, are highly significant.) The positive and negative signs for the variables occurred as one would expect from theoretical and practical experience, and the indications are that these parameters exert a meaningful effect on costs.[10] Table 3.11 uses the latest version of the J79 engine as an example. Total program procurement is 13,000 engines. Thrust is the largest explanatory variable, while Mach number has the largest elasticity. Again, the ΔTOA term significantly affects cost; if it had been zero in this example, the cost estimate would have been about 10 percent lower. It is clear that higher TOA and ΔTOA incur additional development (and component improvement) costs. But such costs may be justifiable if they benefit a weapon system by providing an engine that remains competitive for decades, as the J79 does. This is a matter of judgment concerning military value versus the cost to obtain it.

It is interesting that thrust has a similar elasticity for development and total development, while the Mach number elasticity has tripled in total development compared with development to MQT. A change in Mach number affects total development cost more than it does development to MQT. One interpretation is that the CIP is where the adverse effect of the environment (operational use) is really beginning to show up, and that perhaps not as much money was spent on development as was required to overcome these problems earlier. Mach number is paid for in the continuing development effort. This might indicate that not as much was spent as should have been in development to MQT for afterburning engines. Also, additional Mach number is one of the performance characteristics that was improved and paid for with those CIP funds prior to 1969.

An early planner could use these models to obtain a range of estimates of the total development cost of a new engine program on the basis of these parameters. The quantity term can also be viewed in the context of time, since it would be associated with some production rate and introduction of the weapon system into the force. Time was an important variable in the development to MQT model.

The model of component improvement cost related cost to the thrust, ΔTOA, and the operational span or time that the engine was in operational use. As seen in Table 3.12, the statistics in this case were not as good as the total development equation, particularly in terms of the standard error of the estimate, although again the coefficients were significant. The two models allow alternative ways of obtaining a CIP cost. Cost estimates obtained will differ on the basis of either quantity of engines produced or operational time span of the program. While the cost estimates obtained for the J79 engine from the two approaches are not particularly close, they do indicate a magnitude in excess of development to MQT cost, which is itself an interesting finding.

Thus, CIP=819 -320 =499 million for the J79 example. The actual value at that point in the program was estimated to be about $600 million.

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[10] The costs include the performance improvement and additional applications obtained by a particular program over the years. It was not possible to separate those costs from the data for programs prior to 1969, because data were collected then by function (engineering, test, etc.) rather than by task (deficiency correction or engine growth). Thus, it was not possible in this study to obtain costs related only to reliability growth, for instance. It is hoped such data might be obtained in the future.

Several other approaches for obtaining a CIP cost model were attempted. The ratio of total development to MQT costs, and the ratio of CIP to MQT costs, were investigated as well as a number of additional interesting variables. None of these analyses provided a model as significant as the models shown. One of the variables of interest in one model of the ratio of CIP to MQT cost was the maximum time between overhaul (MTBO) or the average time between overhaul (ATBO); each was used in the model (but not both at the same time) and entered significantly. This implies that the CIP cost ratio was related to improving time between overhaul for engines; the more money spent in CIP, the higher the MTBO and/or ATBO. If these CIP costs can be disaggregated with regard to the varying design objectives prior to 1969, perhaps more information will be forthcoming in future work. This appears to be a fruitful area for additional investigation, because not only is it necessary to understand that more time and money are involved in the continuing development process, but some estimate should be attempted to relate the benefit gained to this CIP money. Questions abound. One particular question appears to be the missing link, which must be addressed in future work: To what measured extent do CIP expenditures lower ownership costs because of improvements in reliability, either at the base or at the depot? How much additional reliability can be purchased for a certain amount of additional money in a specific engine program? How much more time is needed to provide for feedback in the development process, which would allow the introduction of engineering changes into the hardware to make it more reliable in operational use? It should be kept in mind that product improvement money related to increasing the time between visits of an engine to a depot, or related to reducing the removal rate of an engine in the field, while it could greatly reduce operating costs, could also greatly increase the availability of the weapon system. Again, benefits as well as costs must be assessed.

Depot Costs

The primary function of the USAF engine depot is to overhaul engines and accessories to restore them to what is termed a "zero-time" status, allowing the overhauled hardware to be flown again to the maximum time allowed by maintenance policy decisions. The depot also conducts several other engine-related repair activities. They include immediate correction of hardware deficiencies that are causing safety-of-flight problems and could result in grounding of the fleet; minor repairs of engines that do not need major repairs, but such repairs must be accomplished at a depot rather than a base; engine modifications to replace parts that have been obsoleted for deficiency or reliability reasons; repair of reparable parts and accessories removed from returned engines or sent in from the field; and replacement of reparable parts and accessories that are condemned.[11] For new weapon systems entering the inventory, initial spares stockage costs must also be accumulated. To understand the true cost of operating a depot, all of these activities and their associated cost elements must be identified and accumulated.

The primary measure of benefit used in this study is the engine flying hour. In examining the depot portion of an engine life cycle, there are two views of this benefit for estimating costs at the depot: the engine flying hours consumed by the aircraft fleet during operational activity, and the engine flying hours restored to the fleet by the depot repair activity. Under steady-state conditions, it is expected that fleet demand equals depot supply, so that consumed flying hours (demanded by the user) would approximate restored flying hours (supplied to the user from the depot). In any given year, however, this is not necessarily the case. Heavy use could result in more consumed than restored hours, or a large modification program could result in more restored than consumed hours. Moreover, a new engine program consumes more flying hours initially than depot activities restore, as flight operations build up; and over the life cycle as a whole, flying hours consumed exceed flying hours restored because obsolete engines are not repaired prior to disposal. Thus, both flying-hour measures are of interest, particularly when data are limited to only one or two years of experience and such experience can fluctuate widely from year to year in the depot. (See below, "Total Depot Repair Costs," and see App. C for further backup material.)

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[11] System Support Stock Funds for expendable parts must also be included, either as a direct cost or as an added charge to the direct labor-hour cost.

An Engine Single-Overhaul Cost Model. The major depot cost is considered to be the cost associated with the "zero-timing" process for an engine. In that process, the engine is completely disassembled and the parts go off in various directions to be reworked, modified, or condemned and replaced by new parts. Then, as the "engine nameplate" moves down the depot floor, similar parts come back together and are reassembled. By the time the "nameplate" gets to the end of the line, the whole engine is reassembled and is considered to be a zero-time engine; that is, one capable of achieving the full maximum overhaul time allowed for that engine before its next trip to the depot. Most of the parts now making up the engine were probably *not* in the engine when it arrived at the depot.

The cost associated with the whole-engine overhaul is the cost of labor and parts, including the labor for whatever modifications are incorporated into the engine while it is in the depot. The modification kit parts cost is not included; it is a separate account provided as a "free good" to the depot or base, wherever the modification is being accomplished. All of the parts, labor, and overhead, except modification parts incorporated during an engine overhaul, are considered to be within the current cost accounting system, which is the principal source of depot overhaul costs for this study.[13] The cost of repairing the engine's reparable parts is charged as a percentage of the latest purchase price for that part. This percentage is intended to allow some portion for condemnations, parts no longer considered reparable.

Costs associated with zero-timing an engine in the depot have been obtained from the HO36B data. Table 3.13 presents the engine single-overhaul cost in 1975 dollars for FY 1974 overhaul of engines by model. The table also presents estimates of what the engine's current production unit selling price (CPUSP) is or would have been in 1975 dollars (a number of engines are no longer in production). Estimates are on the basis of the last previously known sale and the inflation that has ensued from that time, with some corroboration of these costs from the manufacturers. The

[13] This accounting system was initiated by DoD Instruction 7220.29, *Uniform Depot Maintenance Cost Accounting and Production Reporting System*, October 28, 1968. Data were obtained beginning in 1972, but not until 1974 were they considered of sufficient quality for analysis. The data in this chapter are for FY 1974. The DoD Instruction was recently superseded by DoD Directive 7220.29, October 1975, which now provides the guidance in accounting for and reporting the costs of depot maintenance and maintenance support. Because the first year covered by the Handbook will be FY 1977, data from this new system will not be available for analysis until 1978.

Table 3.13

ENGINE OVERHAUL COST AS A PERCENTAGE OF ESTIMATED CURRENT PRODUCTION UNIT SELLING PRICE, FY 1974
(In 1975 dollars)

Engine	Quantity Overhauled	Overhaul Cost ($ thousand)	CPUSP (est.) ($ thousand)	Overhaul Cost/Engine Procurement Cost (%)
J57-P-19/29	113	49.3	350	14
-21	167	57.2	400	14
-43	358	56.8	350	16
J75-P-17	77	72.2	500	15
J79-GE-15	452	58.9	450	13
-17	265	46.5	450	10
TF30-P-3	137	73.3	900	8
-100	18	165.7	1100	15
TF33-P-3	101	63.7	400	16
-7	207	71.0	400	18
TF39-GE-1	113	174.0	1000	17
TF41-A-1	115	72.6	550	13

table contains costs to overhaul an engine, the engine's current price, and overhaul cost as a percentage of current price. It would appear that it costs in the range of 10 to 20 percent of an engine's current price to overhaul it.

A single-overhaul cost model was obtained for the data presented in Table 3.14. The model is shown in Table 3.15. The overhaul cost is related to the current production unit selling price (CPUSP) of the engine and its physical size: the more expensive the engine, the higher the overall cost, and the larger the engine, the higher the overhaul cost.[13] Production learning and state-of-the-art effects are included indirectly in that they affect CPUSP through the KPUSP model, progress slope assumed, and quantity procured. The data used were for a very limited cross-sectional sample—only one year of data for twelve engines, and one year does not reflect depot learning. Longitudinal data and additional data points are needed to improve the model. An example of the application of the model to the J79 is also presented in the table, showing good agreement with J79 costs. The most important contributor to the calculation is CPUSP, which also has the highest elasticity.

Depot Repair Frequency. An aircraft turbine engine being a mechanical device, its failure history can be expected to approximate a normal distribution: fewer failures for a lower number of flying hours, most failures at some average value of flying hours, and again fewer failures at a higher accumulation of flying hours for a given population of engines. This is portrayed in part (a) of Fig. 3.6, which presents a normal distribution and accumulation of the normal distribution resulting in the classical S-curve. The flying hours obtained increase as the engine

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[13] Note that THRMIL rather than THRMAX was significant. Engines, as a rule, are returned to the depot without afterburners.

Table 3.14

DATA FOR DEPOT SINGLE-OVERHAUL COST MODEL
(In 1975 dollars)

Engine	THRMIL (lb)	CPUSP ($ thousand)	Single-Overhaul Cost ($ thousand)
J57-P-19/29	10,500	350	49.3
J57-P-21	10,200	400	57.2
J57-P-43	11,200	350	56.8
J75-P-17	16,100	500	72.2
J79-GE-15	10,900	450	58.9
J79-GE-17	11,870	450	46.5
TF30-P-3	10,750	900	73.3
TF30-P-100	14,560	1100	165.7
TF33-P-3	17,000	400	63.7
TF33-P-7	21,000	400	71.0
TF39-GE-1	40,800	1000	174.0
TF41-A-1	14,500	550	72.6

NOTE: Data are for FY 1974.

Table 3.15

SINGLE-OVERHAUL COST MODEL
(In thousands of 1975 dollars)

$$\ln \text{SOHC} = -4.27651 + \underset{(5.2)}{0.70741 \ln \text{CPUSP}} + \underset{(3.1)}{0.43157 \ln \text{THRMIL}}$$

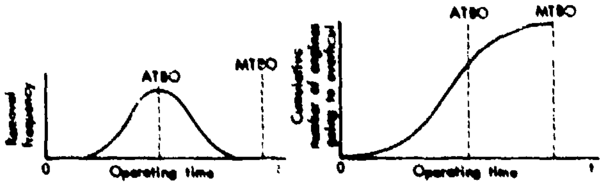
$R^2 = 0.87$
SE = 0.17
F = 31.0 (3,8)

Example: J79 Engine

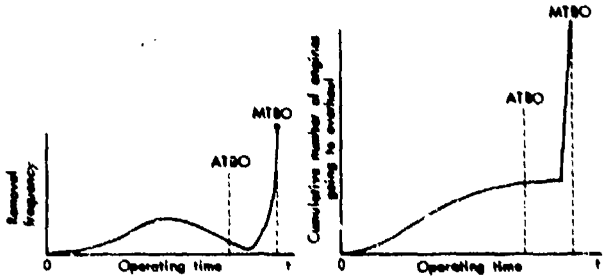
Variable	Value	Calculation	Elasticity
Constant	−4.27651	−4.27651	—
CPUSP	450.0	4.32174	0.7
THRMIL	10900	4.01210	0.4

ln SOHC 4.05733
SOHC = $57.8

NOTE: Based on FY 1974 data in Table 3.14.



Normally distributed engine depot repair when depot removals are all unscheduled -- early engine maturation



Truncated distribution when depot repair includes scheduled removals of matured engine

Fig. 3.6—Impact of MTBO on engine depot removal frequency during maturation of an aircraft turbine engine

matures; thus the normal distribution moves to the right as engine reliability improves. On the average, it is to be expected that engines returned to the depot for unscheduled overhaul will follow this kind of distribution.

The problem during early operational use, when engines are just beginning to accumulate flight experience and the first engines begin to show up at the depot, is to attempt to assess where the small initial sample of early failures fits into the distribution. This is why *appropriate testing* in the development program and early lead-the-fleet testing with a reasonable sample size are so important to begin providing information on the character of the distribution.

Air Force policy has been to set some maximum time between overhaul (MTBO) for a particular engine, at the end of which time it must be returned to the depot for overhaul regardless of how well it is working. As the average time between overhaul (ATBO) experience improves, with improvements to the engine through CIP, the maximum time between overhaul (MTBO) is usually increased. Increasing MTBO is a policy decision based on actual experience with ATBO. At some point, however, the MTBO is usually determined to be long enough and is not to be increased further. One reason may be to prevent the engine from remaining in the field for what is considered too long a time (e.g., five to six years), at the risk of a higher probability of in-flight failure and corrosive damage to parts, which might more than outweigh the cost of more frequent, but less expensive, depot visits. As the engine ATBO continues to improve with no increase in MTBO, the distibution then becomes truncated. This is illustrated in Fig. 3.6(b). Differing experience can be seen for several engines in the Air Force inventory in Figs. 3.7 and 3.8 for the TF30 and the J79. As of 1974, the TF30 appeared to be still maturing, with its ATBO and MTBO continuing to increase, indicating the normal distribution of engines returned to the depot, while the J79, which is considered mature, has not had its MTBO increased for over a decade, and its distribution has become highly truncated.

What can be concluded from this situation? It would appear that overhaul intervals can be lengthened if the service so desires. An on-condition maintenance program, with engine diagnostics and trending provided by some engine health monitoring system, might prove beneficial in such a situation. Such a program would be beneficial not only for extending overhaul intervals in the long term, but also for understanding problems earlier and achieving longer overhaul intervals sooner, which may be the more important reason for on-condition maintenance in the military.

On the other hand, as noted above, there are valid reasons for not extending overhaul intervals to the straining point. As an engine matures, the situation certainly becomes more comfortable to manage. The engine overhaul program is easier to schedule. Failure modes of engines scheduled to those MTBOs are fairly well known. If this is the situation that is desired, then perhaps, at this point in an engine's maturity, consideration should be given to eliminating further CIP efforts and reducing changes and modifications, thereby reducing even further the pertur-

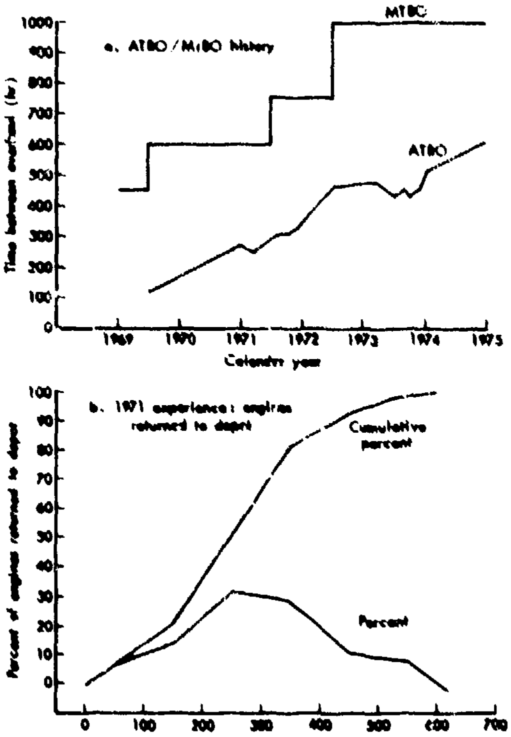


Fig. 3.7—A maturing engine: TF-30-P-3 data

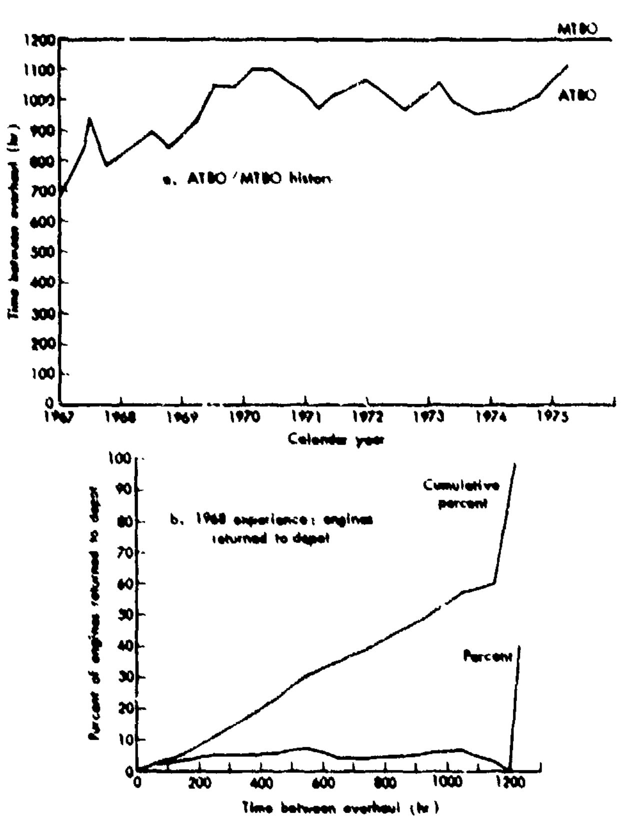


Fig. 3.8—A mature engine: J79-GE-15 data

bation to the depot and maintenance system caused by these changes. The Air Force is in the business of managing thousands of engines, and there may come a time for any given engine model when the marginal improvement to the engine is not worth the perturbation to the repair and supply systems (particularly if attention must be focused on the newer engines entering the inventory) and it is desirable to stop at some MTBO value.[14]

From data obtained from the Air Logistic Centers, it appears that an engine will visit the depot on the average about three to six times in a 15-year life cycle.[15] In general, the lower figure applies to subsonic transports, tankers, and bombers, and the higher figure to supersonic fighters. Frequency also depends on the flying-hour program and severity of the particular mission. For instance, if a transport starts with a 1000-hour MTBO and builds to 5000 hours over its life, and it is expected to fly 500 to 1000 hours in a year, that engine might be expected to go to the depot at least three times. A fighter engine may accumulate only 200 to 300 flying hours in a year, but its MTBO will probably start at several hundred hours and take a number of years to build to 1000 hours or higher. Such an engine might be expected to visit the depot five or six times, depending on how long it takes ATBO to increase during the early years. It must be noted that the visit rate to the depot is determined by actual experience (ATBO), which in earlier years runs about half of MTBO. Thus, the range of three to six times, depending upon application, appears reasonable.

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[14] This truncation caused by fixing MTBO is not a factor in commercial experience today. The airlines' on-condition maintenence policy allows engines that are operating well to continue operating; they are not arbitrarily removed for maintenance at some fixed time interval (at least until maximum time for parts life is reached). The airlines would view such a truncation as an inefficiency that prevented them from getting full flying-hour value from the hardware. Thus, it would be expected that commercial experience would more nearly approximate the classical normal distribution thoughout the ownership life of a particular engine. The commercial policy is not one of "fly to failure," however The airlines require performance monitoring performance trending analyses, and time tracking of parts to achieve on-condition maintenance and fully utilize the modularity feature of new engine design Also, because they accumulate flying hours much faster than the Air Force, they see the average engine much oftener than the Air Force does, despite their on-condition maintenance policy. Even so, there has been some concern raised recently that the airlines may have gone too far with on-condition maintenance. Commercial experience is discussed in Chap. 4.

[15] Estimated from data in OCALC actuarial tables, issued quarterly

An attempt was made to develop ATBO and MTBO models for this study. Obviously, each is highly dependent upon the other. Other variables do not add appreciably to any model in which one is the dependent variable and the other the independent variable. When MTBO is not allowed to enter the ATBO model, or vice versa, then other variables become significant. CPUSP enters both ATBO and MTBO negatively. The implication is that the more expensive engines are also more advanced, more complex, and less reliable, and therefore do not provide as high an ATBO or MTBO as lower-priced engines. The models obtained are presented in Table 3.16 for information purposes only. The statistics are not particularly good. Additional work is needed in this area. It is hoped that improved models can be developed as more and better data become available.

Table 3.16

MTBO/ATBO MODELS

$$\ln \text{ATBO} = 7.79136 - 1.96211 \underset{(3.6)}{\ln \text{CPUSP}} + 1.21296 \underset{(2.2)}{\ln \text{THRMIL}}$$

$R^2 = 0.60$
SE = 0.67
F = 6.8 (2,9)

$$\ln \text{MTBO} = 12.38270 - 2.02554 \underset{(3.1)}{\ln \text{MACH}} - 0.67134 \underset{(1.5)}{\ln \text{CPUSP}}$$

$$+ 0.05854 \underset{(1.4)}{\Delta \text{TOA26}}$$

$R^2 = 0.65$
SE = 0.58
F = 5.0 (3,8)

Total Depot Repair Costs. The full cost of engine depot repair activity is the sum of the costs associated with 1) the zero-time overhaul (including MISTR), 2) minor repair, 3) MISTR repair support to the field, 4) modifications, and 5) the purchase of expendable and reparable parts. It was not possible during this study to obtain costs associated with engine modification kits (BP1100 account) because these funds were not broken down below weapon-system level. These costs should be included in future study efforts to provide an improved perspective of total depot (and base) costs. The other budget accounts, provided by engine family (not by application), include BP15000, Support System Stock Fund (SSSF), and the initial lay-in of spares under BP1600. The BP1600 account was also unavailable for the older engines; it must be retained in the future.

Table 3.17 presents depot cost data for 12 engines, using the H036B report, an estimate for MISTR field support, and an allocation of BP1500 costs. The table lists engine flying hours consumed (EFHC) by the fleet and engine flying hours restored (EFHR) by the depot (as represented by the zero-timing of engines for that year). The ratio between the two varies considerably. Total costs are shown for EFHC and EFHR. The MISTR support and BP1500 are based on EFHC for both costs, since they do directly support the entire flying program in a given year. For the mature engines, it can be seen that the costs are within a reasonably narrow range, thus describing a fairly steady-state situation, whereas for some newer engines (e.g., the TF30, TF39, TF41), the cost comparison between consumed hours and restored hours shows a wider range. Because consumed flying hours substantially exceed restored flying hours for a newer engine program, the cost per restored engine hour represents more closely what the future depot cost will be than does the cost per consumed flying hour.

A total depot cost model was obtained using the data in Table 3.18. The results are given in Table 3.19. The statistical results are good in spite of data and time-period limitations. Again, the independent variables enter with intuitively satisfying signs. Using engine hours restored at the depot in the cost model provided better results than using the cost data related to flying hours consumed by the fleet.

Table 3.19 contains an example for the J79. The single most significant explanatory variable was ATBO, the actual frequency of depot visits. However, the largest contributor to the calculation and the variable with the highest elasticity is CPUSP, with ATBO second. As mentioned for the single overhaul cost model, learning and state of the art are included indirectly through CPUSP. If successful, efforts to increase ATBO by using engine diagnostic systems under an on-condition maintenance policy would reduce depot costs.

What does a depot repair program for an engine cost? From the data analyzed, it appears that a single overhaul costs about 10 to 20 percent of the current procurement cost of that engine (in constant dollars). Modifications to engines inspired by serious flight deficiencies not associated with zero-timing the engine will incur additional costs for that engine at the depot, and the costs will vary with the maturity of the engine. In addition, MISTR support for components returned from the field, and the replacement of condemned reparable parts and accessories during component repair, can add 10 to 100 percent to the total engine program overhaul cost in any given year.

On the average, an engine can go through depot overhaul three to six times or more during a 15-year operational life cycle. Subsonic transport engines fall at the lower end of the range, and supersonic fighter engines at the upper. ATBO is substantially less than MTBO, particularly in the early maturation period of an engine; consequently, average actual repair times are of primary interest for depot costs. Engines seem to go to overhaul more frequently in their earlier years and

Table 3.17

Comparative Depot Costs for Fleet Engine Flying Hours Consumed and Depot Engine Flying Hours Restored: 12 Engines, FY 1974

Item	J57-P-19/29	J57-P-21	J57-P-43	J75-P-17	J79-GE-15	J79-GE-17	TF30-P-3	TF30-P-100	TF33-P-3	TF33-P-7/7A	TF39-GE1/1A	TF41-A-1
Application	B-52D	F-100	KC-135	F-106	F-4C/D	F-4E	F-111	F-111	B-52H	C-141	C-5	A-7D
EFHC[a]	375936	91383	801715	59527	577821	307141	100452	37946	296009	1242214	189336	111405
No. of engines overhauled	113	167	358	77	452	265	137	18	101	207	113	115
ATBO[b]	3666	752	3273	874	948	1057	556	374	2880	6934	1200	333
EFHR[c]	414258	125584	1171734	67298	428496	280105	76172	6732	290880	1435338	135600	38295
EFHR/EFHC	1.1	1.37	1.46	1.13	0.74	0.91	0.76	0.18	0.98	1.16	0.72	0.34
HO36B ($ million)	5.6	9.6	20.3	5.6	26.6	12.3	10.0	3.0	6.4	14.7	19.7	8.3
Overhaul ($/EFHC)	15	105	25	94	46	40	100	79	22	12	104	75
Overhaul ($/EFHR)	14	76	17	83	62	44	131	446	22	10	145	217
MISTR[d] ($ million)	4.2	7.2	15.2	2.6	5.6	2.6	4.3	2.0	1.9	4.3	2.0	5.5
MISTR ($/EFHC)	11	79	19	44	10	9	42	53	6	3	11	49
BP1500 allocated ($ million)	3.8	0.9	8.0	1.1	6.4	3.4	12.4	4.7	1.2	5.0	1.9	13.3
BP1500 ($ EFHC)	10	10	10	19	11	11	123	123	4	4	10	119
Totals:												
$/EFHC	36	194	54	157	67	60	265	255	32	19	125	243
$/EFHR[e]	35	165	46	146	83	64	296	622	32	17	166	385

[a] Engine flying hours consumed.

[b] Average time between overhaul.

[c] Engine flying hours restored.

[d] Management of items subject to repair. This row also contains significant minor-repair costs for the TF30-P-3, TF30-P-100, and TF41-A-1 engines.

[e] Sum of Overhaul ($/EFHR), MISTR ($/EFHC), and BP1500 Allocated.

Table 3.18

DATA FOR DEPOT TOTAL COST MODEL: H036B MODIFIED DATA, FY 1974 (In 1975 dollars)

Engine	ATBO (hr)	CPUSP ($ thousand)	OPSPAN (qtr)	ΔTOA26 (qtr)	DCEFHR ($/EFHR)
J57-P-19/29	3666	350	75	4.7	35
J57-P-21	752	400	76	4.7	165
J57-P-43	3273	350	73	4.7	46
J75-P-17	874	500	60	-2.5	146
J79-GE-15	948	450	55	11.9	83
J79-GE-17	1057	450	29	11.9	64
TF30-P-3	556	900	30	6.2	296
TF30-P-100	374	1100	12	6.2	622
TF33-P-3	2880	400	56	-0.9	32
TF33-P-7	6934	400	45	-0.9	17
TF39-GE-1	1200	1000	18	4.1	166
TF41-A-1	333	550	20	-7.0	385

Table 3.19

DEPOT COST PER ENGINE FLYING HOUR RESTORED: 12 DATA POINTS, FY 1974 (In 1975 dollars)

$$\ln \text{DCEFHR} = 2.76182 - \underset{(10.17)}{0.90604 \ln \text{ATBO}} + \underset{(4.16)}{1.2607 \ln \text{CPUSP}}$$

$$+ \underset{(2.24)}{0.01104\ \text{OPSPAN}} - \underset{(1.87)}{0.02245\ \Delta\text{TOA}}$$

$R^2 = 0.975$
SE = 0.22
F = 67.6 (4,7)

Example: J79 Engine

Variable	Value	Calculation	Elasticity
Constant	2.76182	2.76182	—
ATBO	1057	-6.30893	0.9
CPUSP	450	7.70217	1.3
OPSPAN	29	0.32016	0.4
ΔTOA	11.8	-0.26491	-0.3
ln DCEFHR		4.21031	
DCEFHR		67	

cost more to overhaul in later years, because parts in older engines are more often condemned and replaced; the situation must therefore be viewed in a total context, not solely in a mature-engine steady-state context.

When the single overhaul cost, added support costs, and frequency of depot visit are combined, the results indicate that total depot costs for an engine during a 15-year operating span can exceed its procurement cost.

Base Costs

As mentioned earlier, specific weapon-system-related costs are significantly lacking at the base level. Bases apparently do not have a single integrated data source for all costs related to engine maintenance. Accordingly, this study uses data from a variety of sources to estimate the base labor and parts costs for selected engines in the Air Force inventory. (See App. D. for additional discussion.)

Engine costs at the base are related to maintenance labor, parts, and support for the following activities: unscheduled flight-line maintenance; unscheduled maintenance in the shop, including removal and replacement of engines and accessories; periodic scheduled maintenance (including base-installed modifications); engine test and checkout before installation; and removal and replacement when an engine is to be returned to the depot. Existing maintenance data indicate that from one-half to two maintenance man-hours are expended per flying hour on the engines of a variety of weapon systems. In using such data, however, the analyst must take care that they cover all engine-related work—not only unscheduled maintenance, but also scheduled maintenance and engine-related accessories—and that they exclude repair of aircraft-related engine-mounted accessories (QEC items). Also, such data represent labor utilized. When available engine shop personnel are counted, the maintenance labor available is on the order of one-half to two maintenance man-years per possessed engine on the base; this can translate into three to six maintenance man-hours per flying hour, depending on the particular weapon system and its flying hour program.

Available manpower is what the Air Force is paying for in terms of total maintenance labor cost. A policy has been determined concerning the necessary manning for a wartime contingency (the number of personnel required to support the weapon system in a wartime environment), and the Air Force is paying for that level of labor, even if it is not fully utilized in peacetime.

At present, one approach to the base cost of maintenance labor for an engine is to examine the Unit Detail Listing. As indicated above, data from several selected bases indicate that maintenance labor will vary from one-half to two maintenance man-years per possessed engine, depending on the particular engine. Some administrative and support costs must be added to this direct labor cost (a 50-percent add-on is assumed here). Thus, one maintenance man-year is estimted to cost $10,000 in direct labor and an additional $5000 in indirect costs, for a total of $15,000 per maintenance man-year. Expendable parts must be estimated (a range of from more than $1000 to less than $5000 per engine per year is indicated for the first-line engines, again depending on the engine)[16] from an examination of RMS, depot supply, and engine manager accounts. It appears that although this total base cost may be less than depot costs for most engines, it is a significant amount.

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[16] For instance, the J79-GE-17 on the F-4E at Seymour Johnson AFB, North Carolina, requires about 2/3 maintenance man-year per possessed engine for the base, and supply accounts indicate about $1500 per engine per year in expenditures for FY 1975. On the basis of 200 flying hours per engine per year, a cost of $57.50 per engine flying hour would be estimated for base support.

An effort was made to relate base costs obtained from estimates of propulsion shop manning and supply expense to parameters of interest in order to obtain a base cost-estimating relationship (CER). A range of costs were obtained (see Table 3.20). The maintenance man-years per possessed engine ranged from 1/2 to 1 for most engines in the inventory. Supply expense varied as shown in the table. An average value was then used in generating CERs. The specific data used to generate the base cost model are presented in Table 3.21. The results, presented in Table 3.22, are interesting in indicating explanatory variables, but the model should be viewed cautiously because of the nature and limitations of the data. For base maintenance costs, MTBO (the policy-determined maximum time between depot overhaul) was most significant, entering the relationship negatively. Thus, successful efforts to extend MTBO would reduce base costs, since periodic scheduled inspections are directly related to MTBO and are a significant portion of propulsion shop activity. OPSPAN entered positively; the longer an engine is in operational service, the more costly it is to maintain at the base. CPUSP entered positively; the more expensive the engine, the more it costs to maintain at the base. It would appear, then, that efforts to increase MTBO (on-condition maintenance using engine health monitoring or diagnostics systems) and decrease the engine selling price could work toward lowering base maintenance cost. As discussed previously, production, learning, and state-of-the-art effects could be considered as included indirectly through CPUSP. Again, it must be emphasized that this model represents only the grossest cost estimates for the base. An improved model must await better data from new or improved base data collection systems and detailed examination of base-level data.

Table 3.20

BASE LABOR AND MATERIAL COSTS PER ENGINE FLYING HOUR CONSUMED, FY 1974 DATA
(In 1975 dollars)

Engine	Estimated Range of Maintenance Man-years per Possessed Engine	Estimated Range of Material Expense per Possessed Engine	Total Engines in Inventory	EFHC per Year	Average EFHC per Year per Engine	Range of Base Cost per EFHC
J57-P-19/29	0.5 - 1.0	1000 - 2000	2328	376,936	162	53 - 106
J57-P-21	0.5 - 1.0	1000 - 2000	767	91,383	119	71 - 142
J57-P-43	0.5 - 1.0	1000 - 2000	2434	80,715	323	26 - 52
J75-P-17	0.5 - 1.0	1000 - 2000	338	59,527	176	48 - 96
J79-GE-15	0.5 - 1.0	1000 - 2000	2874	577,821	201	42 - 81
J79-GE-17	0.5 - 1.0	1000 - 2000	1570	307,141	196	43 - 86
TF30-P-3	0.5 - 1.0	2500 - 5000	530	100,452	190	53 - 106
TF30-P-100	0.5 - 1.0	2500 - 5000	236	37,946	161	62 - 124
TF33-P-3	0.5 - 1.0	1000 - 2000	880	269,009	336	25 - 50
TF33-P-7/7A	0.5 - 1.0	1000 - 2000	1700	1,242,214	731	12 - 24
TF39-GE-1/1A	1.0 - 2.0	2500 - 5000	425	189,336	445	39 - 78
TF41-A-1	0.5 - 1.0	2500 - 5000	520	111,405	214	47 - 94

Table 3.21

DATA FOR BASE MAINTENANCE COST MODEL, FY 1974
(In 1975 dollars)

Engine	MTBO (hr)	CPUSP ($ thousand)	OPSPAN (qtr)	BMC EFHC ($/EFHC)
J57-P-19/29	4000	350	75	80
J57-P-21	1000	400	76	107
J57-P-43	4000	350	73	39
J75-P-17	1200	500	60	72
J79-GE-15	1200	450	55	63
J79-GE-17	1200	450	29	65
TF30-P-3	1000	900	30	80
TF30-P-100	600	1100	12	93
[illegible]-3	4000	400	56	38
[illegible]7	9000	400	45	18
TF39-GE-1	3000	1000	18	60
TF41-A-1	750	550	20	71

Table 3.22

BASE MAINTENANCE COST PER ENGINE FLYING HOUR CONSUMED:
12 ENGINES, FY 1974 DATA
(In 1975 dollars)

$$\ln \text{BMCEFHC} = 3.50819 - \underset{(4.47)}{0.47457 \ln \text{MTBO}} + \underset{(2.24)}{0.01299\ \text{OPSPAN}} + \underset{(1.64)}{0.56739 \ln \text{CPUSP}}$$

$R^2 = 0.79$
SE = 0.26
F = 10.0 (3, 8)

Example: J79 Engine

Variable	Value	Calculation	Elasticity
Constant	3.50819	3.50819	—
MTBO	1200	-3.36474	-0.5
OPSPAN	29	0.37671	0.5
CPUSP	450	3.46633	0.6
ln BMCEFHC		3.98649	
BMCEFHC		54	

Spare Engines

Spare engines add approximately 25 to 50 percent to the installed engine inventory in the Air Force, and thus account for at least 20 percent of the total procurement cost of engines for a weapon system. They also have the effect of diluting the number of expected flying hours per engine over the life cycle. (See App. E for further backup data and discussion.) For example, an engine designed to operate for 5000 flying hours within a specified life cycle will probably fly only around 4000 hours, on the average, if it has a 25 percent spares ratio. Table 3.23 presents data for 15 Air Force engines. The spares ratio appears to be application-oriented, in that the lower percentages appear to apply primarily to subsonic transport and bomber aircraft and the higher percentages to attack and supersonic fighters. The cost of spare engines can be handled directly when computing the total cost for quantity of engines procured during a weapon system's lifetime, assuming a spare engine ratio. Spare engines bought during the same period as the installed engines should have the same progress slope applied, and indeed should help reduce the cost of future engines. The spares merely add to the total quantity of engines to be bought. But how many spare engines should the Air Force buy?

Table 3.23

SPARE ENGINE INVENTORY, FY 1975

Engine	Total Inventory	Active Installed Inventory	Spares Ratio
J57-19/29	2328	1040	2.24
J57-21	767	482	1.59
J57-43	2434	1634	1.49
J57-55	523	326	1.60
J57-59	3125	2586	1.21
J75-17	338	195	1.73
J75-19W	297	150	1.98
J79-15	2874	2158	1.33
J79-17	1570	1104	1.42
TF30-3	530	340	1.56
TF30-100	236	164	1.44
TF33-3	880	758	1.16
TF33-7	1435	1114	1.29
TF39-1/1A	425	308	1.38
TF41-1	511	342	1.49

There is a specific computation for obtaining the number of spare engines a weapon system is expected to require.[17] On the basis of factors such as programmed flying hours, number of installed engines on the aircraft, number and location of operating bases, and where certain repairs of the engine are to be made, a requirement is established for a specific number of spare engines to fill the pipeline at the base and between the base and the depot. Specific numbers of days are estimated for the time it will take a base to turn an engine around and a depot to process an engine at overhaul. The spare engines serve as replacements for failed engines that are removed for repair. A fill-rate objective is specified in terms of the ability to meet the demand for a spare engine. If the demand cannot be met, it is called a back order, which is defined as an aircraft requiring an engine. Given the fill rate and a certain number of spares at a base, an expected effectiveness rate can be calculated—that is, the rate at which aircraft have their spare engine requirements satisfied and again become operational. A confidence level is also associated with this process. For combat aircraft, the confidence level is presently required to be 80 percent. Spare engine requirements are estimated on the basis of the minimum quantity of engines essential to support the programmed peacetime or wartime operation, whichever is greater. Since wartime flying is usually programmed at a higher rate, it is to be assumed that the spares are applicable to the wartime posture. Thus, spare engines are intended to reflect wartime requirements in terms of a fill-rate objective and effectiveness rate at [illegible] confidence level. Usually, more spare engines are purchased early in a new weapon system program, and then phased down to the computed requirement as experience is gained. But the computed wartime requirement could still be higher than is necessary, particularly if appropriate consideration is given to attrition and duration of the conflict. (A study under way at Rand concerning this issue indicates this to be the case.)

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[17] The standard computation procedure is DODI 4230.3, *Standard Method for Computation of Spare Engine Procurement Requirements.* The Systems and Resources Management Advisory Group also studied the spare engine situation and recommended reexamination of spare engine procurement with the idea that the Air Force might be able to reduce spare engine procurement without degrading combat support capability.

No parametric model was obtained in this study to enable an early planner to predict the appropriate spares ratio for a particular application.

Other Costs

Other operating and support costs besides depot and base maintenance (and fuel and attrition) contribute to the total life-cycle cost of an engine. They include:

1. Transportation
2. Ground support equipment
3. Management
4. Training
5. Facilities.

The above costs appear to add not more than 5 percent to all costs previously discussed (not including initial recruitment training or a major facility expenditure). Thus, increasing the total life-cycle cost for an engine by 5 percent should encompass all of the costs identified here for acquisition and ownership.

SUMMARY OF MILITARY ENGINE LIFE-CYCLE COST MODELS

The TOA methodology for relating performance to development schedules has been incorporated into cost-estimating relationships (CERs). TOA and ΔTOA were investigated along with other variables felt to be important. Reasonable CERs were obtained for military engine development and procurement costs, where homogeneous, disaggregated cost data were available from the contractors for a 25-year period. Without this type of data, meaningful relationships could not have been obtained. The approach was to investigate variables considered important in the development and procurement phases of a new engine. The approach was then extended to the ownership phase of the engine life-cycle to obtain more comprehensive models for total engine development, component improvement, and depot and base maintenance costs. The model results are summarized in Table 3.24.

Again, in all the cost models studied, the variables have entered the relationships in an intuitively satisfying manner. The signs of the coefficients are in the right direction in terms of what an engine designer would expect concerning changes in these variables and the resultant impact that such changes would have on cost. For instance, in the development cost model, development time entered

Table 3.24

MILITARY LIFE-CYCLE ANALYSIS
(In 1975 dollars)

State-of-Art Trend $R^2 = .96$ SE = 6.9 F = 92.0 (5, 20)	$TOA26 = -856.38 + 110.10 \ln TEMP + 11.41 \ln TOTPRS - 26.08 \ln WGT - 16.02 \ln SFCMIL$ (5.6)[a] (3.1) (5.1) (2.8) $+ 18.37 \ln THRMAX$ (2.8)
Development Cost ($M) $R^2 = .96$ SE = .18 F = 55.7 (4, 9)	$\ln DMQTC = -1.3098 + 0.08538 DEVTIME + 0.49630 \ln THRMAX + 0.04099 \Delta TOA26 + 0.41368 \ln MACH$ (7.6) (7.1) (4.9) (2.3)
Component Improvement Cost ($M): $R^2 = .88$ SE = .29 F = 60.5 (3, 22)	$\ln CIP = -2.79026 + 0.78862 \ln THRMAX + 0.04312 \Delta TOA26 + 0.00722 OPSPAN$ (9.1) (5.7) (2.5)
Total Development Cost ($M) $R^2 = .94$ SE = .16 F = 114.8 (4,29)	$\ln TDC = 0.97355 + 1.23809 \ln MACH + 0.07345 \ln QTY + 0.40386 \ln THRMAX + 0.00918 \Delta TOA26$ (10.3) (6.8) (8.5) (2.1)
1000th Unit Cost ($M) $R^2 = .95$ SE = .215 F = 63.0 (4,13)	$\ln KPUSP = -8.2070 + 0.70532 \ln THRMAX + 0.00674 TOA26 + 0.45710 \ln MACH + 0.01804 \Delta TOA26$ (9.2) (2.8) (2.6) (2.4)
Cumulative Production Quantity Cost ($M) $R^2 = .97$ SE = .22 F = 501.7 (6, 81)	$\ln PRQTYC = -7.8504 + 0.8697 \ln QTY + 0.82204 \ln THRMAX + MFRDUM + 0.01858 \Delta TOA26$ (45.) (24.) (6.) (5.) $+ .34478 \ln MACH + 0.00277 TOA26$ (4.) (2.4)
Depot Maintenance Cost Per Engine Flying Hour Restored ($/EFHR) $R^2 = .97$ SE = .22 F = 67.6 (4, 7)	$\ln DCEFHR = 2.76182 - 0.00604 \ln ATBO + 1.26074 \ln CPUSP + 0.01104 OPSPAN \quad 0.02245 \Delta TOA26$ (10.2) (4.2) (2.2) (1.9)
Base Maintenance Cost Per Engine Flying Hour Consumed ($/EFHC) $R^2 = .79$ SE = .26 F = 10.0 (3,8)	$\ln BMCEFHC = 3.50819 - 0.47457 \ln MTBO + 0.01299 OPSPAN + 0.56739 \ln CPUSP$ (4.5) (2.2) (1.6)

NOTE: See List of Symbols for definitions of terms.

[a] t statistics.

positively, indicating that the longer the program, the higher the cost.[18] The other variables in this model also indicate rational results. Thrust enters positively. The larger the engine, the higher the development cost. ΔTOA and Mach number enter positively; they are related to the state-of-the-art increment (or additional time increment required) to be obtained in the development and complexity of the engine (reflecting the technology reach in the program) due to the environment in which the engine has to operate. Thus, the development cost model and the 1000th Unit Production Cost model are basically the same as previously reported [1], except for conversion to 1975 dollars. The total development and component improvement cost models reflect the addition of several data points and therefore differ slightly from the models previously reported. Both are included so that alternative methods can be used to compute total development cost. One model depends on quantity of engines procured, while the other depends on the total time in operational service (OPSPAN).

Several variables had to be introduced in developing the production quantity cost model. One was a manufacturer's dummy, required because of the sharply different accounting practices used by one of the manufacturers before 1971. The most significant variables are quantity and THRMAX. Certainly, quantity should be most significant in this type of model, and the thrust level is a measure of the physical size of the engine. Again, alternative methods of computation can be employed for obtaining total production cost: either the production quantity model, which contains industry average learning, or the 1000th Unit Production Cost model and an assumed process slope that can reflect a manufacturer's learning experience.

A model for total depot cost per engine flying hour restored at the depot (by zero-timing the engine) was obtained as shown in Table 3.24. The variables found to be significant are the average time between overhaul (ATBO), current production unit selling price (CPUSP), operating span (OPSPAN), and increment of time-of-arrival at the initial MQT (ΔTOA26). Again, they enter with intuitively satisfying signs for the dependent variables. For instance, successful efforts to extend ATBO would reduce depot costs. The cost model using engine hours restored at the depot provided better results than using the cost data related to fleet-consumed flying hours. The difference between restored and consumed flying hours can be substantial in a given program.

An attempt was made to relate base costs to parameters of interest in order to obtain a base cost-estimating relationship. The results are interesting in indicating explanatory variables, but the model should be viewed cautiously because of the nature and limitations of the data. For base maintenance costs, MTBO (the policy-determined maximum time between depot overhaul) was most significant, entering the relationship negatively. Thus, efforts to extend MTBO would reduce base costs, since base periodic scheduled inspections are directly related to MTBO and are a significant portion of propulsion shop activity. OPSPAN entered positively; the longer an engine is in operational service, the more costly it is to maintain at the base. CPUSP entered positively; the more expensive an engine, the more it costs to maintain at the base. The model provides an estimate of base maintenance cost per flying hour consumed by the fleet. In a 15-year life-cycle cost estimate, consumed engine flying hours will exceed restored engine flying hours because an engine is not returned to the depot to be restored when it is about to be scrapped.

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[18] It must be noted, however, that a minimum development time—on the order of four to five years—for a new engine program must be associated with this estimating relationship, since in the extreme, this relationship could result in zero development cost at zero time. Obviously, it takes some amount of time to develop any new engine, however simple it may be in terms of available technology; the model therefore must incorporate a minimum development time.

TOA does not enter directly into the depot and base models, but does enter indirectly through CPUSP, thus providing some measure of state-of-the-art impact on cost. (ΔTOA provides a residual effect on depot cost but is not in the base cost model. It also enters indirectly through CPUSP.) CPUSP entered both the depot and base models; thus, it would appear that attention to designing an engine to a production unit cost would reap benefits in the ownership area.

AN EXAMPLE

Using the models derived, Table 3.25 presents a comparison of life-cycle cost breakdowns for hypothetical fighter engine programs of the 1950s, 1960s, and 1970s. In spite of increases in development and procurement costs of engines (in constant dollars) from one decade to the next, the ownership cost portion dominates and tends to represent an increasingly larger portion of the total.[19] Depot maintenance cost is the reason for this trend. Miscellaneous costs were estimated to be approximately 3 percent of total costs for this example. Table 3.25 indicates that total life-cycle cost has more than doubled from the 1950s to the 1970s and that the depot is accounting for an increasing portion of that larger cost. Presently, depot costs are the largest part of engine life-cycle costs. The 1970s engine is significantly more advanced in technology, and is larger in thrust and faster in Mach number, than the 1950s engine, and those improvements are what the military is paying for in attempting to obtain better weapon systems.

An additional calculation is shown for the 1970s engine for a case in which ATBO/MTBO has been doubled. The results show a significant ownership saving if the improvement can be realized. The models cannot show how to obtain this improvement, but do indicate that it would be worth considerable additional development or CIP effort (or some new maintenance concept such as on-condition maintenance) to achieve it.[20]

These theoretical examples, although intended to reflect real engines acquired in these decades, were constructed to show trends on a comparable engine-program basis from decade to decade. Real engine programs will not necessarily indicate similar results for a particular decade in their designs, and programs are significantly different from the assumptions shown in the table.

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[19] Overall ownership cost currently represents two-thirds of total life-cycle cost, where ownership includes CIP and whole spare engines, but not fuel and attrition, for the fighter-engine example presented. Similar results were also obtained for current transport engines.

[20] This example is concerned with possible variations in ownership costs. Reference 19 presents examples of how these models might be applied in looking at changes in the process of acquiring engines

Table 3.25

LIFE-CYCLE COST BREAKDOWNS FOR HYPOTHETICAL FIGHTER ENGINES OF THE 1950s, 1960s, AND 1970s

	Cost for Engine with 750 ATBO, 1200 MTBO						Cost for Engine with 1500 ATBO, 2400 MTBO	
	1950s		1960s		1970s		1970s	
Cost Element	$M	%	$M	%	$M	%	$M	%
	Itemized Cost Breakdown							
RDT&E	311.7	8.9	360.3	7.2	428.1	5.4	428.1	7.0
Procurement								
Install	983.3	27.9	1429.7	28.5	2273.1	28.9	2273.1	36.9
Spares	245.8	7.0	357.4	7.1	568.3	7.2	568.3	9.2
CIP	252.2	7.2	330.6	6.6	428.0	5.4	428.0	7.0
Depot	1066.4	30.3	1708.2	34.0	3052.6	38.8	1629.0	26.5
Base	558.1	15.9	690.2	13.7	897.9	11.4	646.2	10.5
Miscellaneous	102.5	2.9	146.3	2.9	229.4	2.0	179.2	2.9
Total[a]	3520.0	100.0	5022.5	100.0	7877.5	100.0	6152.0	100.0
	Cost per Engine Flying Hour Consumed[b]							
Acquisition	216		298		450		450	
Ownership	371		539		863		575	
(Base and depot maintenance)	(271)		(400)		(658)		(379)	
Total LCC	587		837		1313		1025	

NOTE: Assumed for all programs:

1975 dollars
5-year development
15-year operations
Advanced engines
90% learning (production)

6 M EFH consumed by fleet
5 M EFH restored by depot
1935 engines produced (including flight test and spares at 25%)
No fuel or attrition included

It is also assumed that the future will behave in a manner similar to the past.

[a] May not add exactly because of rounding.

[b] Average cost for total program.

Chapter 4

COMMERCIAL AIRCRAFT TURBINE ENGINE LIFE-CYCLE EXPERIENCE: A COMPARISON WITH MILITARY PRACTICE

Commercial airline peacetime operations provide an environment in which benefits can be measured more quantitatively and related to life-cycle costs. The airlines offer a service, providing a degree of safety and dependability, at a price. Their success can be measured over time in their ability to stay in business, earn a profit, meet some amount of competition, and grow in a regulatory climate. To some degree, then, it is possible to measure success quantitatively much as costs are measured.

COMMERCIAL LIFE-CYCLE PROCESS

The airlines purchase engines and engine parts as someone might an automobile and its replacement parts. Once the initial choice is made, the buyer then has less latitude in purchasing replacement parts. The airlines do not pay directly for the development of engines and airframes as a specific cost as the military do, but in reality their purchase prices cover all or some portion of that development cost. The manufacturer's price for new engines and parts covers not only the cost of design, development, and manufacture, but also the company's profit, incremental costs for component improvement, IR&D, and a margin to cover the warranty the company provides to the airline. The warranty may take the form of a guaranteed maximum material cost per flying hour to the airline for a certain period of time and/or number of flying hours. The manufacturer is liable for some portion of material cost exceeding the maximum. Engine companies, for example, may guarantee to repair or replace an engine part if it fails within an initial period, and to refund some portion of the cost for that part up to some additional flying time, after which the engine company is no longer liable. These warranties vary, depending on the coverage the airline desires and is willing to pay for, and on the engine company's desire to conclude a sale. The actual value of a warranty is therefore a matter of negotiation between the airline and the manufacturer for each particular situation, since there is a wide area of interpretation concerning primary fault and secondary effects and who pays for what portion of the total cost involved.

It is readily apparent that the life-cycle process differs substantially for commercial and military engines. The military pay for development, component improvement, and IR&D separately, and they are required to oversee these expenditures. There is no warranty coverage for military hardware except in the case of failure of a brand-new item. The IR&D and CIP are funded separately, but in reality are obtained by the engine companies as add-ons to the selling price of a military engine, once the basic selling price and procurement quantities for a given year have been established, and the total cost and apportionment of IR&D and CIP programs have been approved.

TIME-OF-ARRIVAL FOR COMMERCIAL ENGINES

The technology for the design of aircraft turbine engines—at best an imprecise art—has improved steadily during the past three decades in a continuing quest for higher quality. During this evolutionary development, the demand for performance has dominated military acquisition, and usually under highly constrained schedules; the manufacturer's effort to meet both performance and schedule requirements exposes engine programs to the risk of serious cost growth, while relegating to lesser importance other quality characteristics of durability, reliability, maintainability, safety, and concern for environmental effects.

Commercial engines are designed to a different balance of criteria. Higher performance is still desirable, but safety and cost considerations make durability, reliability, and maintainability critical characteristics. Government-mandated safety requirements are a basic consideration in commercial flight, with cost as the strong second consideration. Since the same manufacturers provide both military and commercial products, the design differences between the two are not a matter of a different technology base, but of adapting the available technology to fit the two sets of circumstances.

Commercial engines procured by the airlines over the years have benefited significantly from previous military experience, as indicated in Table 4.1. Lately, this trend has been changing; the JT9D was almost totally a commercial development by Pratt and Whitney (although the technology base still reflects a substantial military contribution).

How different are commercial demands from military demands concerning the quality of an engine? The TOA approach was employed to help answer this question.

Table 4.1

MILITARY PREDECESSORS TO COMMERCIAL ENGINES

Company	Commercial Engine	FAA Certification Year	Military Predecessor	Model Qualification Test (MQT)
Pratt & Whitney	JT3C	1958	J57	1952
	JT4A	1959	J75	1956
	JT3D	1960	TF33	1960
	JT8D	1963	J52	1961
	JT12	1960	J60	1960
	JT9D	1969	None	—
	JT10D[a]	1979[b]	None	—
General Electric	CJ805-3	1960	J79	1956
	CJ805-23	1961	J79	1956
	CJ610	1963	J85	1961
	CF700	1964	J85	1961
	CF6	1970	TF39[c]	1969
	CFM56[a]	1978[b]	F101[c]	—

[a] European collaboration.

[b] Estimated.

[c] Gas generator technology applied to commercial derivative.

A commercial engine data base of 11 points was obtained and run in the TOA26 model. The detailed data for military and commercial engines are in Table 4.2. The results for the 11 data points in TOA26 are shown in Fig. 4.1. The commercial trend line lies below and appears to be approaching the 45-degree-line military model as time increases. The implication is that commercial engines are more "conservative" than their performance-oriented military counterparts. It also appears that the commercial line is converging with the military model, indicating that commercial engines may be tending to approach military engines in the future. Indeed, some engine designers feel that commercial technology could surpass military technology in the future, especially if noise abatement requirements and smoke elimination requirements are explicitly considered in the TOA index. Another possible factor is the absence of new military programs started in the early 1960s (see Table 3.2). As previously noted, all commercial engines were direct derivatives of military programs until development of the Pratt and Whitney JT9D. The JT9D is the first example of a major new U.S. aircraft turbine engine entering commercial service with no prior military experience.

Table 4.2

TECHNOLOGY DATA FOR COMMERCIAL U.S. TURBINE ENGINES

Engine	Turbine Inlet Temp. (°R)	Thrust Max. (lb)	Weight (lb)	Pressure Term (lb/ft^2)	SFC (lb/hr/lb)	MQT (qtr)	Period of Development Initiation
JT3C	1995	13,500	4234	11,050	0.78	59	Late 1950s
JT4A	1985	15,800	5020	10,200	0.80	59	Late 1950s
JT3D	1995	17,000	4150	11,050	0.52	71	Late 19[illegible]s
JT8D	2180	14,000	3160	13,600	0.59	81	Late [illegible]
JT12	2000	2,700	465	5,525	0.96	71	Late 1950s
CJ805-3	2100	11,200	2800	11,050	0.83	71	Late 1950s
CJ805-23	2100	16,100	3800	11,050	0.56	77	Late 1950s
CJ610	2060	2,850	399	5,780	0.99	82	Early 1960s
CF700	2160	4,125	725	5,525	0.65	87	Early 1960s
JT9D	(a)	(a)	(a)	(a)	(a)	107	Late 1960s
CF6	(a)	(a)	(a)	(a)	(a)	112	Late 1960s

[a] Deleted for security or proprietary considerations.

The 11 commercial engines were then added to the data base of 26 military engines, and an equation was obtained that uses the combined data base and employs a dummy variable for the commercial engines to differentiate them from the military. The results are shown in Fig. 4.2. The indication is that commercial engines are more conservative than military engines. The dummy variable has a positive value of about ten quarters, indicating that commercial engines are about 2-1/2 years behind military engines in their TOA. This model is presented in Table 4.3 together with a comparison of the J79 engine and its commercial counterpart,

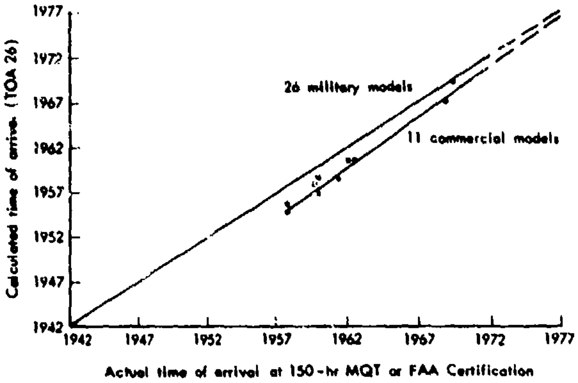

Fig. 4.1—Comparison of military and commercial aircraft turbine engine technology

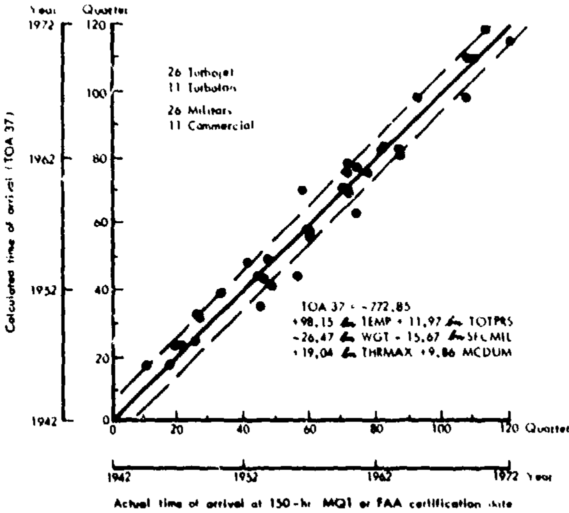

Fig. 4.2—Military and commercial turbine engine time of arrival

Table 4.3

COMMERCIAL AIRCRAFT TURBINE ENGINE TIME-OF-ARRIVAL (TOA)

$$\begin{aligned} \mathrm{TOA37} = -772.85 &+ \underset{(6.7)}{98.151 \ln \mathrm{TEMP}} + \underset{(3.5)}{9.860\,\mathrm{MCDUM}} + \underset{(3.9)}{11.970 \ln \mathrm{TOTPRS}} \\ &\underset{(6.6)}{-26.465 \ln \mathrm{WGT}} - \underset{(3.5)}{15.668 \ln \mathrm{SFCMIL}} + \underset{(3.5)}{19.038 \ln \mathrm{THRMAX}} \end{aligned}$$

$R^2 = 0.964$
SE = 0.1
F = 134

Examples: J79 and CJ805-3 Engines

	J79		CJ805-3		
Variable	**Value**	**Calculation**	**Value**	**Calculation**	**Elasticity**
Constant	-772.85	-772.85	-772.85	-772.85	—
TEMP	2160	+753.59	2100	+750.82	1.3
MCDUM	0	0	1	+9.86	—
TOTPRS	18056	+117.32	11050	+111.44	0.2
WGT	3225	-213.80	2800	-210.06	-0.4
SFCMIL	0.87	+2.18	0.83	+2.92	-0.2
THRMAX	15000	+183.07	11200	+177.50	0.3
TOA37		69.5		69.6	
MQTQTR		57			
FAA certification				71	
TOA		+12.5		-1.4	

the CJ805-3.[1] The lag could be explained in either of two ways: Either the commercial engine achieved the same performance level as the military but received certification 2-1/2 years later; or, for the same development milestone, the commercial engine design traded off reduced performance for greater durability, reliability, and maintainability, which affect safety and cost. It does appear that engine designers apply the technology base differently in designing a new commercial engine.

This finding has significance for the current military trend of designing to a life-cycle cost, because the trend will require engine designers to make quantitative tradeoffs among aspects of quality other than performance. Since this model is attempting to relate time to multiple design objectives, a crucial task for future work is to quantify the characteristics of durability, reliability, maintainability, safety, and environmental impact so that they can be introduced into a time-of-arrival model along with performance considerations.

COMMERCIAL OWNERSHIP

The primary concern of an airline is to make a profit, and the primary oper-

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[1] This TOA approach, using the dummy to distinguish the design objectives of commercial versus military practice, was also used to estimate a commercial development cost model. Only two commercial engine development data points were obtained. These costs are considered highly proprietary by the manufacturers and are usually not available for outside study efforts. Terms that were found to be significant in the military development cost-estimating relationship were also important in commercial development, allowing for the 2-1/2-year time lag.

ational benefit measure for an airline is aircraft utilization. For engines, utilization is usually expressed in flying hours or operating cycles. The commercial flying-hour experience is considerably dfferent from the military. The airlines follow established routes with known demand rates for flying-hour segments and takeoffs and landings over a given calendar period. The military has varying requirements, except perhaps for a portion of the fairly well-scheduled MAC fleet. The airlines accumulate engine operating hours faster than the military, even for comparable aircraft. The airlines fly about three times more hours in a given year than the MAC fleet aircraft, and ten times more than supersonic fighter aircraft.

OPERATIONAL PRACTICE

Commercial operational practices and procedures also differ from the military. Operationally, the airlines require pilots to devote considerable "tender loving care" to their aircraft. The throttle is used only to the extent made necessary by gross weight, field length, altitude, and temperature for takeoffs and landings. On almost all Air Force aircraft, there is no way to determine how much hot-time the engine sees during a known mission profile, although there has been some initial work on engine diagnostic systems that count throttle excursions. (The F100 engine on the F-15 aircraft has such a counter, but it is not yet working well in operational practice.) Squeezing out the last percent of power is considered very costly to engine hot-section life. Airlines require flight crews to monitor engine performance in flight and to supply data for trending analysis of engine performance after each flight. Careful throttle management enables the airlines to achieve important dollar savings by trading performance for temperature (and thus parts life). The Air Force could do the same. Since the military operation of an engine is even further up on the higher end of the power curve (approaching maximum performance), even a nominal reduction in throttle excursions could yield a very significant improvement in parts life. (Several examples are already available for TAC and SAC aircraft.)

MAINTENANCE PRACTICE

Commercial maintenance practice has been extolled as an example from which the military might benefit. Airline maintenance practice today has turned away from the military's hard-time philosophy (certain actions are taken at certain times regardless of how well the engine is operating) toward what is generally termed on-condition maintenance.

There is some semantic confusion concerning the meaning of on-condition maintenance. Current airline maintenance procedures actually fall into three areas of consideration: maintenance of life-limited, high-time parts; condition monitoring of certain non-safety-of-flight parts for which there are no fixed time limits; and on-condition maintenance of critical safety-of-flight parts that require regular periodic inspections. The various airlines cause some confusion by using these terms somewhat differently, but in general they distinguish between on-condition maintenance and condition-monitored maintenance related to the level of inspection activity and impact of the part on safety-of-flight.

The intent of the on-condition maintenance program is to leave the hardware alone as long as it is working well and symptoms of potential problems are not developing. This philosophy is *not* one of "fly-to-failure" when safety-of-flight items are involved. This maintenance program is expected to reduce the shop visit rate, determine which parts are causing removals and at what time intervals, increase the engine's accumulation of flying hours and cycles by maintaining its availability on-wing, reduce secondary damage resulting from serious failures, and maintain and improve the normal distribution of failures expected for engines.

Prolonging the interval between shop visits for maturing commercial engines is equivalent to increasing the average time between overhauls in the military. The result of this action is to prevent the truncation of the engine overhaul distribution caused by fixing the maximum allowable operating time between overhauls and the subsequent resulting large increases in the engine removal rate when maximum hard-time overhaul is reached. The commercial practice could therefore provide insights to the military in terms of what parts are determining failure rates and how CIP funds might best be apportioned among various engine problems.

On-condition maintenance has several specific requirements: (1) periodic on-aircraft inspection of engine safety-of-flight areas at ground stations (borescoping, X-ray, oil sampling and analysis, careful examination of the engine); (2) engine performance checks and data-gathering in flight, using such data for trending analysis at a central data processing center (usually at the main overhaul facility) to anticipate problems before they occur; and (3) tracking of critical parts by part number to keep account of the amount of operating time and operating cycles the parts have undergone.

When an engine problem is discovered or anticipated from trending analysis, the engine is removed from the airframe and repaired at a base if possible (by replacing a part or module, which is then returned to the shop); or the entire engine is sent back to the shop; or the aircraft is scheduled for a flight to the maintenance base so that the engine can be removed and another engine installed overnight with no loss of scheduled flight time. It is estimated that 90 percent of engine repair activity is performed at the shop; very little fixing of hardware is done at bases except removal and replacement of engines or modules or of major parts easily reached with minimum disassembly. (The base also performs other tasks primarily concerned with the ground inspections, and handles lube, oil, and maintenance associated with day-to-day activities.) It may be asked why the Air Force cannot operate in this manner. The reason is that the airlines operate in a relatively stable peacetime environment. Some Air Force units may be able to operate in a similar manner, but others must be prepared to be self-sufficient in an overseas wartime contingency and thus are required to maintain a larger labor force at the base level.

When a commercial engine is returned to the shop, the data system is expected to furnish the engineering and maintenance people with records of how much operating time has accumulated on particular parts, so they can judge whether to fix only the part that is broken (or that they anticipate will break shortly) or to fix other parts as well while they have the engine in the shop. They attempt to rebuild the engine to some minimum expected operating time.

Newer commercial engines are of modular design. "Modular" means that the engine can be readily separated into major subassemblies. The intent is to add flexibility to maintenance procedures at the shop and at the base. Engines can be removed and replaced overnight and modules can be "swapped out" at a base in several days, with only the modules returned to the shop for repair. One result is that airlines turn engines around faster than military depots (15 to 30 days versus 45 to 90 days), and consequently require substantially fewer spare engines.

The Air Force has begun to procure modular-designed engines; the F100 engine on the F-15, and the F101 on the B-1, are examples. The Air Force is now implementing a modular engine maintenance information system like that of the airlines for keeping track of the operating time on parts and for helping in decisions concerning the operating life appropriate for each module and engine. The Air Force will have to be able to do this kind of analysis at the depot and base if it plans to adopt the commercial maintenance philosophy regarding modular engines and, especially, regarding on-condition maintenance.

Maintenance experience and skill levels are very high for the airlines in their central shops. Most mechanics are FAA-qualified, have a long continuity in service, and with their years of experience get to know the individual engines and aircraft, since the fleet is not so large for a given airline. The civilian labor force at the Air Force depot also has considerable continuity of service, but the base inventory and the current practice of completely disassembling an engine during overhaul and reassembling it with different parts prevents them from getting to know individual engines—besides which, the engine changes its identity every time through the depot. It is not clear how much of an edge this gives the airlines, but airline people consider it substantial. The commercial work force is also more flexible about scheduling overtime during peak periods and laying off during slumps. The military depot does not have this flexibility in the short term.

Several airline officials have expressed concern that perhaps they have gone too far too fast with on-condition maintenance as applied to current high-bypass-engine experience. Their worry is that they might be merely postponing certain problems to a later date. They believe they are obtaining more operating hours, but at a cost: When an engine finally does return to the shop, perhaps more has to be done to it in terms of parts replacement than if it had come in sooner. The problem is to determine the "optimum" point. The military attempt to do so by setting an engine MTBO at some point that the user and supplier believe is optimum in terms of operational availability on the one hand, and the amount of work required when it is returned to the depot, on the other hand. The choice lies between the two extremes; a short-fixed-time philosophy is one, and on-condition maintenance running to failure or almost to the anticipated point of failure is the other. There may be some optimum intermediate point derived from a combination of hard-time and on-condition maintenance, and this optimum could vary, depending upon the individual airline or military situation. One airline's (or service's) optimum is not necessarily another's because of differences in route structure and operating conditions (mission), utilization of the fleet, economic environment, and so forth. At any rate, it would appear desirable for the military to move away from its strict hard-time philosophy, but no doubt there is some point on the on-condition maintenance spectrum beyond which it may not be desirable to go for the sake of economic efficiency. Appropriate data are required to assist in seeking this optimum.

COMMERCIAL ENGINE COSTS

What does it cost the airlines to own and operate their commercial engines? The question is more difficult to answer than would first appear, even though manufacturers preserve a great deal of engine cost data over a substantial period of time for their cost analyses. Airlines are also required to provide certain cost data to the CAB, separated into certain cost categories.

Because accounting practices, operations, and economics vary among airlines, however, only the individual airline will know fully what its costs are under its own accounting practices, route structure, operating environment, seasonal adjustments, and economic conditions.

Therefore, difficulties arise in attempting to use airline cost data directly. The purchase price of an engine that an airline reports to CAB may reflect the cost of the entire pod, which is the total installed engine in its nacelle ready for mounting on the aircraft wing, or it may reflect the bare engine and certain spare parts. It may also include, as in the case of reported Air Force contract prices, spare parts and accessories, technical data, and field service costs. Thus, it may be difficult to use the aggregated data reported to CAB to arrive at standardized procurement costs that will be comparable among the commercial airlines. At least an estimate can be obtained, however, if it is known whether the purchase was for a bare engine or a podded engine, and if some idea can be gained of what additional costs are involved in the purchase price.

The matter of proprietary information can be a further stumbling block. To gather information on military engines for this study, it was necessary to go to the manufacturers for disaggregated, homogeneous, longitudinal data. They were willing to supply military data on a proprietary basis, but they are not willing to supply commercial cost data at all, except in the most unusual circumstances and then only on a very limited basis.

In sum, the analyst faces the dual difficulty of determining the content of the CAB data and of obtaining information the airlines and manufacturers consider highly proprietary. Thus, the major problem in comparing commercial and military engines is generating comparable costs. At present, the most pressing need is to understand what the commercial cost data actually include; nor is it sufficient to do so for only a one-year or two-year cross-section. Cost analysts in both the engine industry and the airline industry agree that five to seven years worth of historical data are needed to gain a reliable picture of the trend for a particular piece of equipment. This appears to be true for both technical and economic reasons.

ANALYSIS OF AVAILABLE DATA

Figure 4.3 depicts a rough breakdown of typical 14-year life-cycle costs for the older first- and second-generation commercial turbojet and turbofan engines. New third-generation high-bypass engines may be different in terms of cost magnitude and proportions, and their cycle may be extended in order to cover their higher costs, with depreciation spread over more years—perhaps 16 rather than 14. The figure reveals that 75 to 80 percent of cost is ownership. It should be recalled, however, that the procurement cost of the engine includes allocations for development and IR&D, and ownership costs also include, besides CIP and warranty add-

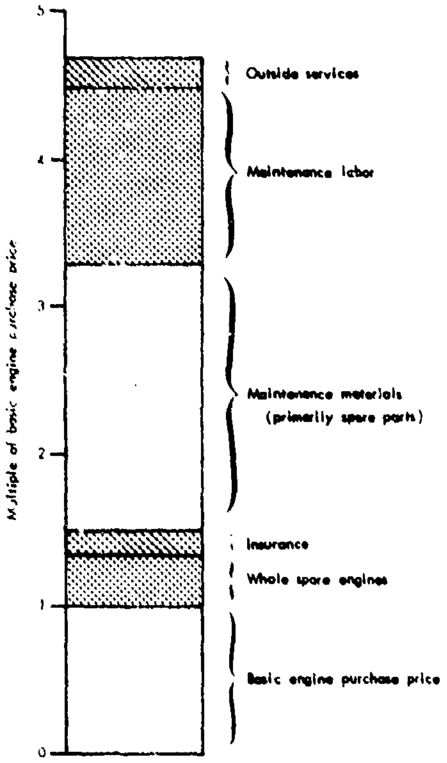

Fig. 4.3—Typical 14-year life-cycle costs for first- and second-generation commercial turbojet and turbofan engines (from Ref. 5)

ons, a charge for development; consequently, acquisition and ownership costs are not cleanly defined even for airlines. It is interesting to note from the figure that an airline buys an engine twice over in spare parts alone during its operational lifetime.

Data obtained from five commercial airlines in the course of this study indicate that the older and smaller turbofan engines such as the JT8D and the JT3D are costing between $50,000 and $100,000 per shop visit for engines that have been operating for 2000 to 4000 hours, while the newer and larger high-bypass engines such as the CF6, JT9D, and RB-211 are costing between $100,000 and $200,000 per shop visit for engines that have been operating for 1000 to 2000 hours. The cost range appears to be affected by the size of the engine, the state of the art, engine maturity, usage since the last shop visit, and airline policy concerning refurbishment to a minimum time for next shop visit expectation. The costs are quite different from those obtained from the military for comparable engines with similar operating experience. Airline shop costs are apparently fully burdened[a] and reflect around 90 percent of base and shop costs combined. At the military depot, a cost increment of at least 50 to 100 percent must be added to the major overhaul cost to obtain the total depot cost per engine processed in a given year.

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[a] Including all allocated materials, back shop labor, and overhead, except for major modifications, which are treated as investment rather than operating expense for tax purposes.

What does it cost to maintain a commercial engine? From the data presented, ownership constitutes 75 to 80 percent of total life-cycle cost (not including fuel). The first- and second-generation commercial engines are estimated to have a peak cost of around $40 to $80 per flying hour for ownership and $50 to $100 per flying hour total. Steady-state costs with the advent of maturity fall to a range of $20 to $30 per flying hour for engine maintenance. Peak costs appear to be two to three times steady-state costs. A total of about 35,000 to 45,000 operating hours in a 14-to-16-year period is expected. New third-generation high-bypass engines will peak at well over $100 per flying hour if the same percentage breakdown applies. The airlines hope that long-term steady-state ownership costs can be reduced to around $40 to $50 per flying hour when maturity is attained for these new-generation engines. Since these engines are of higher technology, with at least twice the thrust and considerably improved specific fuel consumption, they are expected to be well worth the higher cost to the airlines in the service they will provide with the new wide-bodied transports.

In examining the available commercial cost data over a number of years, a general cost profile trend is distinguishable. Figure 4.4 presents actual data that appear to corroborate such a pattern. A hypothetical cost profile is shown in Fig. 4.5. It presents expected cost patterns on the basis of consumed and restored engine hours with peak, average, and steady-state values indicated. Also shown are two general problem areas that seem to occur in engine maturation: an early peak (occurring usually because of problems in the hot section in the engine's maturation) and later on, an additional hump on the way to steady-state conditions (some cold-section problems tend to show up later). Shop visit rates show the same pattern

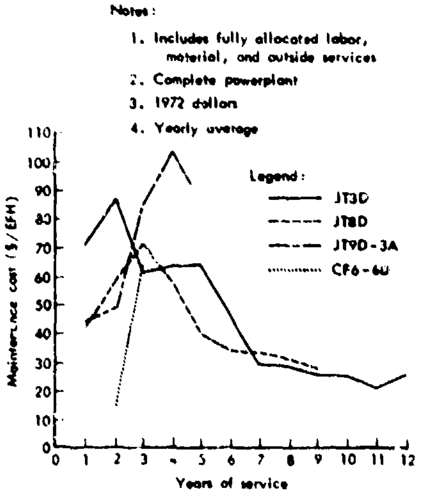

Fig. 4.4—Total maintenance cost of complete powerplant

SOURCE: Hq USAF, *Report of the Procurement Management Review of Aircraft Gas Turbine Engine Acquisition and Logistics Support*, Washington, D.C., February 1976.

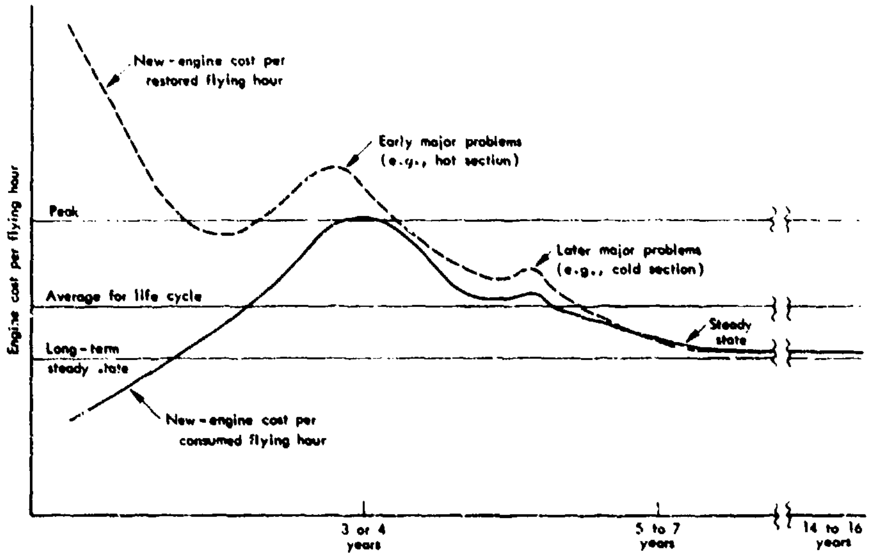

Fig. 4.5—Cost profile for commercial turbine engines

(leading the reported cost data by six to nine months because of reporting delays). The JT9D, operating since 1970, apparently is approaching maturity and will be an interesting example to watch as an indicator of cost differences between the current generation of high-bypass engines and previous generations' experience. It does appear that the high-bypass engines are at least twice as costly to operate. The question still to be answered by the operators is whether or not they will be as profitable as expected in the long term. They were expected to return their investment and increase airline profits when they were purchased in the late 1960s. The difficulty has been the slower than expected increase in air transportation growth in the early 1970s. One indication that things may be different for a high-bypass engine is that some airlines are now using 16 years as the depreciation period for tax purposes rather than 14 years, because these newer engines are not accumulating flying time as rapidly as the older engines at similar points in their life cycle. Consequently, the extra time is needed to achieve the expected 35,000 to 45,000 operating hours on the hardware.

In short, it is possible to construct a cost profile for the life-cycle of an engine. The data examined here are consistent with the general trend indicated regarding maturation and steady-state operation. This commercial cost profile of peak, steady-state, and average costs should be helpful in attempting to understand overall military life-cycle costs, which should behave similarly (at perhaps a higher cost level). The use of only cross-sectional data to estimate costs for a given engine can be misleading if the engine's relative position in its overall life cycle is not understood, and if the data are heavily weighted to the steady-state situation, when average costs are needed to determine overall life-cycle cost.[3]

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[3] In the military models developed in this study, both the depot and base equations contain the term OPSPAN, which controls for the time effect to some extent. However, the data were heavily weighted by programs that had arrived at fairly steady-state conditions.

Chapter 5

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

This study of policy considerations in the life-cycle process of aircraft turbine engines has attempted to bring into focus factors relevant to the benefits and costs associated with acquisition and ownership. Chapter 2 discussed theoretical considerations. Chapter 3 dealt with the military process in detail. Chapter 4 addressed the commercial process for comparative purposes in an attempt to identify practices that the military might profitably adopt. The objective has been to highlight the information and methodology an early planner requires in determining effective tradeoffs and thus arriving at policies appropriate to various phases of the engine's life cycle. Examples of calculations for current engines and applications to new engines have been provided. This chapter summarizes the study's results, conclusions, and recommendations. (For a succinct treatment of this chapter, see the author's executive summary, R-2103/1-AF.)

DESIGN OBJECTIVES AND DATA REQUIREMENTS

The technology for the design of aircraft turbine engines—at best an imprecise art—has improved steadily during the past three decades in a continuing quest for higher quality in terms of performance, durability, reliability, and maintainability. During this evolutionary development, the acquisition of turbine engines for military aircraft has been primarily performance-oriented. The manufacturers who have provided engines to the military throughout this period have maintained their business bases by responding to and meeting the needs of the customer within certain limits, and the military customer has demanded performance. Furthermore, he has usually demanded performance under a highly constrained schedule, thus exposing engine programs to the risk of serious cost growth while relegating to lesser importance the characteristics of durability, reliability, and maintainability.

When a customer makes other demands, as in commercial transport, engines are designed to criteria other than performance. Safety and cost considerations make durability, reliability, and maintainability critical characteristics for commercial airlines. Since the same manufacturers provide both military and commercial products, engine design is not a matter of different technology, but of using the available technology differently to fit the circumstances.

Designing an engine to performance, parts-life, and safety requirements is fairly well understood by engine designers; even designing to a production-unit cost is understood to some extent. But designing to *military life-cycle benefit and cost criteria* is not presently understood to the extent that it should be, particularly in terms of the appropriate durability, reliability, and maintainability in the operational context of military ownership. In short, the art of designing a military aircraft turbine engine to a life-cycle cost is still in a primitive stage, if it exists at all.

The difficulty for the designer lies in not fully understanding the appropriate tradeoffs because of a lack of detailed information concerning 1) how the military use the engine, and 2) how operational problems are related to the design. (If a part breaks, for example, the designer needs to understand not only how it broke, but why it broke.) The designer does not have at his disposal data relating the military benefits and costs from operational and support activities in sufficient detail to enable him to analyze the tradeoffs among the various design objectives in a total military life-cycle context.

Now that total life-cycle cost is becoming an increasingly important consideration and the demands of the military customer are apparently changing, the engine designer will require more detailed cost/benefit information to perform the necessary design tradeoffs. But he cannot lay hands on that information overnight. Currently, the available military operational and cost data are heterogeneous, aggregated, and cross-sectional; to enable effective design tradeoffs involving total life-cycle costs, the data must be homogeneous, disaggregated, and longitudinal. The data must be clearly defined; each data element must retain identity and consistency over time; all relevant cost elements must be included and broken down to the appropriate level of detail; and the data must be available over a long enough period of time so that the engine's maturation process can be understood. In the commercial area, for instance, cost analysts in both the engine industry and the airline industry agree that five to seven years worth of historical data are needed to gain a reliable picture of the trend for a particular piece of equipment.

When fairly homogeneous, somewhat disaggregated, and reasonably longitudinal data were available—for example, 25 to 30 years of RDT&E and production cost data from engine contractors covering a variety of programs—interesting analytical and methodological results were obtained. When the cost data were heterogeneous, aggregated, and cross-sectional—two or three years worth of selected ownership cost elements—analytical and methodological efforts have been less successful but still very promising. It will be necessary to develop some methodology for total life-cycle analysis if early planners are to obtain and evaluate the leverages that might exist between the costs of early acquisition and later ownership and their resulting impacts on operational capability. The needed data must be obtained. Several new data systems or modifications to existing systems are now being implemented to improve this situation; but organizations learn to adapt to the data systems imposed on them while still perpetuating their customary ways of doing things, which is one of the problems of existing systems in the actual data they obtain and provide for analysis. The best solution may be one of periodic sampling to obtain the data needed for specific weapon systems at particular times in their operational life span.

A METHODLOGY FOR LIFE-CYCLE ANALYSIS

Valuable insights can be obtained for both a weapon system and the component through a life-cycle analysis of a new weapon system at the system level and at the component level. Macro and micro viewpoints corroborate each other in both "top-down" and "bottom-up" analyses. The relative importance of the component to the weapon system must be ascertained in terms of contribution to performance as well as resource consumption; the data can be disaggregated so as to assess the major components, such as airframe, engine, avionics, weapons, and ground support, and the relative magnitudes of these various programs. It is recommended that other components, particularly airframe and avionics, be analyzed similarly to the engine. It is more difficult to obtain CERs at the component level than at the weapon-system level.

This study has presented methodology for relating the time-of-arrival of a bundle of performance characteristics sought in a military engine at the model qualification test date for that engine. The methodology was made possible because 25 years of disaggregated, homogeneous, longitudinal data were available from the engine manufacturers.

MILITARY LIFE-CYCLE FINDINGS

How much does it cost to acquire and own a military engine? It would appear that, even today, nobody really knows the full cost of an engine's life cycle. No study to date has clearly defined the cost elements and the associated actual life-cycle costs for an ongoing engine program; nor has anyone formulated a sound methodology for obtaining such cost estimates in any detail, to be used in the early planning for new engines. Nobody really understands the full magnitude and correct proportions of costs attributed to life-cycle phases for an engine. Although development and procurement costs are fairly well understood, it is still difficult to predict the cost of a new engine program with high accuracy. The results of this study indicate that the magnitudes of development, procurement, and ownership costs are considerably higher than previously estimated. Not only the magnitude, but also the composition of ownership costs as related to a weapon system, are not well understood. The extent of the confusion can be seen from the range of results obtained in this study, where it was necessary to use cross-sectional data in an attempt to obtain some measure of operating and support costs for engines in the current USAF inventory.

Can we at least answer the question: What is it costing the Air Force to operate a particular engine today? This study does shed additional light on the overall area of engine total life-cycle cost and it provides a more reasonable range of cost estimates for the current inventory. This study was not undertaken with the expectation that 100 percent of the total life-cycle cost could be obtained. It was hoped, however, through direct and indirect means of data analysis and with some measure of confidence, to identify and capture the major share of costs and to ensure that no significant cost—one that could influence a policy decision—would be missing from the data.

The range of *operating and support costs* obtained for all front-line USAF engines in the present inventory varied from $30 to $750 per engine flying hour during FY 1974, with estimates of particular engine application varying by a factor of two to three. The wide range of engine operating and support costs can be attributed to differences in the following:

- Physical characteristics
- Operating environment
- Technological content
- Technological advance sought

- — Maturity of engine program
- — Age of specific hardware
- — Utilization rate
- — Data source
- — Methodological definitions and assumptions
- — Acquisition policy
- — Operational policy
- — Logistics support policy.

The general findings of this study are that:

- More money is spent in ownership than in acquisition of engines (not including fuel and attrition in a 15-year operational life span.
- Progress has been made in modeling ownership costs for depot and base maintenance. The model presented in this study found the current production-unit selling price and the average or maximum time between overhaul to be the most significant variables. Although time-of-arrival terms did not enter into these models, these terms are strong determinants in the production unit selling price model and thus affect the results, although indirectly.
- Leverages do exist such that, during the operational life span, spending additional money earlier in an engine's life cycle can yield substantial reductions in operating and support sums later on. This was true of past systems, and it is even more true of newer high-technology systems. Procurement costs for new systems have greatly increased, and operating and support costs have kept pace with them; they appear to be at least as large as procurement costs and, in some cases, appear to account for an increasing percentage of total life-cycle cost.

The extent of the tradeoff between acquisition and ownership costs is still not known, in terms of how much improvement in engine quality could be obtained for additional sums spent earlier in development, and the extent to which that improvement would reduce ownership costs later on in specific operations and support areas. Previous experience indicates that, usually, reliability significantly improves when additional time and money are allocated during the engine's initial operational maturation. In turn, this improved reliability strongly affects mission capability and support costs.

- Assuming a 15-year life span, Component Improvement Programs (CIP) conducted during the engine's operational life can cost as much as it did to develop the engine to its initial 150-hour Model Qualification Test (MQT). An engine design has an inherent quality, but once the detailed design is transformed to hardware, it remains for testing and operational experience to bring out that quality to the fullest. Testing is an absolute necessity, and it must embody the appropriate time, conditions, and procedures so that major problems are discovered and corrected as quickly as possible within the limits of sound engineering practice. It is clear that CIP have improved engine reliability, partly because of the past practice of placing tight time constraints on the development process and leaving a considerable portion of the maturation process until operational usage.

- There comes a point in an engine's maturation, however, when consideration should be given to significantly reducing CIP. That point arrives when the engine has attained a reasonable reliability, but continual changes are perturbing the system and causing difficulties that are no longer worth overcoming for the sake of trifling improvements in capability. The J79 experience during the last five or six years, for example, indicates that even though CIP has been continuing, MTBO has not increased, removal rates of engines from aircraft at bases have not decreased, ATBO has not appreciably increased, and average age of installed engines has not increased. This is a comfortable situation to manage, both at the base and depot levels, and it could be stated that the CIP is helping the J79 to grow old gracefully. If the Air Force wished to maintain this situation, would there be a problem without the CIP? The chances are that there would not be, and life would probably be simpler for everybody. Engineering changes continue to come from the CIP program for the J79; they require some new modifications and the purchase of additional parts, with resulting perturbations in the system. The reliability of the new parts is uncertain, nor is it known how they will affect older parts they are related to. Suddenly, in place of known reliabilities and familiar stockage procedures, the AFLC is confronted with a changed situation in which it takes time to learn new failure rates and perhaps 18 months to order new parts. For such reasons, the airlines increasingly reject engineering changes, except for safety, as the engine achieves maturity after five to seven years of operational experience. The defenders of CIP point out, however, that CIP are justified by another of their useful functions: They restore spec performance to reworked parts at the depot by devising new repair techniques as hardware gets older. To investigate the validity of such arguments, an analysis of depot reject rates should be performed to assess the relationship of temperature and stall margin for newly overhauled engines. Perhaps some modest deterioration could be allowed because the engine tends to get hotter and lose stall margin as it gets older and loses its performance internally. There is, of course, a tradeoff between cost and performance, durability, reliability, and maintainability. One possibility is to design and test a new engine to higher performance levels, if a particular level is to be required for the weapon system and to be held at each depot visit. This is an alternative to relaxing the depot spec.

With the new engine development process advocated by the Air Force, product reliability should be considerably enhanced at the beginning of operational service and should attain higher levels at an earlier point in the life cycle. It is recommended, therefore, that with the new development procedure and with an expanded data base for tracking the engines, consideration be given to stopping CIP after an engine has achieved a satisfactory reliability level.

- When all relevant depot costs are accounted for, they can exceed engine procurement costs. It is important to obtain all relevant depot costs for support of an engine program and to understand the full cost of overhauling an engine, as well as all other support [illegible] depot levels to field maintenance. It is recommended that data be analyzed [illegible] able, on the benefit/cost improvements seen in the product at the depot due to increased development effort resulting from the new development procedure. On-condition maintenance and the new concept of modular maintenance should also be analyzed, and tests should be conducted to determine the value of on-condition maintenance and power management in extending the reliability of engine parts and reducing repair costs.

Operational policies concerning mission training, base-level support, depot support, and engine spares for wartime contingencies add significantly to cost, particularly when compared with commercial practice. Further study of these areas is recommended. For instance, it is important to understand, at the component level, the effect on operating and support costs exerted by maintaining specific manning levels at various types of bases for contingency purposes. TAC, because of rapid deployment considerations, may have reason to be oriented toward base support of equipment. SAC and MAC, on the other hand, because they are not expected to operate from overseas bases in a steady-state situation, may operate more efficiently if they emulate the commercial airlines, with engine maintenance largely centralized at a single shop.

- There is a significant time lag in implementing improved data collection systems, and sufficient data are not now available for accurately determining life-cycle benefits and costs. Consequently, the ability to design to a life-cycle cost is in the future. Meanwhile, for new weapon systems currently being contemplated for the 1980s, a philosophy of designing an engine to a production unit selling price for the engine quality desired is a reasonable alternative.

Even if the data were available and a methodology were developed to perform a meaningful life-cycle analysis for a new engine, a basic problem of implementation still remains. Decisionmaking during weapon-system selection has been highly centralized. The need of the user has been qualitatively assessed in terms of an expected threat. Although the using and supporting organizations furnish high-level inputs during concept formulation, they lack real influence during the later validation and development process and therefore cannot maintain pressure to see that their realistic needs are met as they face the problems of operating and supporting the new system. The new Acquisition Logistics Division in AFLC is an attempt to remedy this situation.

COMMERCIAL LIFE-CYCLE FINDINGS

A number of commercial practices suggest possible avenues toward life-cycle improvement for the military in procurement, operations, maintenance, and cost management. In particular, engine-power management, on-condition maintenance, appropriate testing for modifications, and cost tracking and profiling appear to be beneficial to the airlines, although they cannot always fully quantify benefits and costs.

The Air Force has taken beginning steps in some of those directions, most notably in power management to cut down on hot time. Some aircraft are having their throttles restricted to necessary uses, and on excursion counter has been installed on the F100 engine in the F-15 aircraft (although it is not yet working very well in operational practice). Power management is being applied not only in MAC, where it might be expected because of the similarity to commercial experience, but also out of necessity in TAC, because of engine reliability and durability problems. These are worthwhile actions, but the Air Force does not appear prepared to collect data from this experience for comparison with the previous situation in order to assess what power management is worth for different applications. The airlines themselves do not know that worth precisely, particularly for high-bypass engines, which started off with power management from the beginning; however, they do have some data from earlier JT3D and JT8D experience that indicate a significant extension of hot-parts life. If the airlines believe power management is worthwhile, it should be even more so for the military and their performance-dominated situation. It is recommended that the Air Force conduct tests and collect the data to assess the value of power management across their front-line inventory in MAC, SAC, and TAC.

On-condition maintenance has yielded cost savings for the airlines, not only in terms of level of work in the shop, but also in aircraft availability. The Air Force is now considering moving in this direction with several new engine programs that are capable of using on-condition inspection procedures, data trending analysis, and modular maintenance concepts. Careful analysis of data as they become available should indicate the value of this trend for future engine designs, and indicate whether the Air Force should move away from its "hard-time" philosophy or whether, when an engine reaches an acceptable maturity level, "hard-time" is the appropriate policy. There is an "optimum" time buildup for engines under an on-condition maintenance policy: Several airline officials have expressed concern that they may have gone too far too fast with this type of maintenance. Their worry is that an engine may reach the point where it is more expensive to replace parts after many hours of use than to rework parts after fewer hours of use. The Air Force depot faces this same tradeoff, along with the perturbations caused by introducing continual parts changes to a very large engine population.

The airlines conduct lead-the-fleet testing for modifications to their equipment. Manufacturer-proposed product improvements are increasingly rejected (except for safety) as years and maturity of the product increase in commercial service. The Air Force should review its own CIP policy concerning changes as the engine matures, as well as its lead-the-fleet policy regarding the appropriate lead time necessary to introduce changes into the fleet. Lead-the-fleet aircraft should be two years ahead of average experience for military engine programs.

For a modular engine design, the interactions between related modules and how those interactions may degrade performance attained in the field are still imperfectly understood. This is true even though the modules may have passed their inspection tests at the depot. The airlines are gaining experience in this area, however. There is also a relationship between the cost of overhaul and the flying hours it restores. The more new parts put into the engine, the higher the probability that it can stay out in the field longer. The military have not demonstrated or analyzed that relationship to any extent. It has been seen in commercial practice, but the airlines do not necessarily decide in favor of the higher cost and added flying hours. They choose some optimum for the particular situation.

RECOMMENDATIONS

This study, in conclusion, has arrived at the following recommendations.

- Efforts to develop the methodology presented in this study should be continued as better data become available. The aim is to formulate a comprehensive life-cycle model, incorporating military and commercial objectives, that will improve cost estimates and confidence in those estimates.
- Until a comprehensive model is developed, it is recommended that the Air Force use the methodology in its current form to estimate the costs of future engines (that is, of any engines that are acquired in the same manner as in the past), and to measure how costs might change if acquisition and ownership were conducted differently.
- In the basic design iteration process, when a new weapon system is under consideration in the conceptual phase, the military user should be brought in and given an important role in selecting requirements for the final design. Commercial airlines are totally involved in the early design of the product they buy. They know their requirements, their route structure, and the way they are going to use the equipment. It is equally important for the military user to do the same and to make his needs known.
- The Air Force should consider conducting detailed tests for all current aircraft and new aircraft entering the first-line inventory, to determine the price it must pay for the last percentage increment of performance in terms of loss in aircraft availability and engine reliability, and cost of engine repair and overhaul. Once the tradeoffs are established, the Air Force may still not wish to give up that last few percent, but the cost of sacrificing a degree of durability can be explicitly recognized in future engine design selections and developments. Engine design must take into account mission profiles, engine duty cycles, specifications, accelerated service testing, engine monitoring, and the usage of the data base. An accelerated lead-the-fleet service test might fit into the new Air Force development concept in terms of establishing a reliability trend for an engine. The Air Force is moving in this direction. Previous SAB studies arrived at similar recommendations. It was the intent of this study to present the framework for analysis as improved data become available throughout the life cycle.
- It is recommended that Air Force begin collecting and *preserving* disaggregated, homogeneous, longitudinal data at both depots and bases, associated with specific engine types. Currently, efforts have just begun to separate base maintenance costs by weapon system; and existing studies of total depot costs for engines do not consistently include, along with overhaul of whole engines, the cost of parts repair during overhaul, the cost of expendable parts, the full cost of replacing condemned reparables, and the repair of components received directly from the field and returned to the field.

A review of operating and maintenance techniques and policies for all using commands is desirable to assist in bringing on-condition maintenance and power management to fruition. Engine diagnostic systems could assist in obtaining significant improvements. Progress is already being made in this area.

The Air Force can expect to face a problem in the matter of *Incentives* for the decentralized developing, using, and supporting organizations responsible for carrying out new weapon-system acquisition, operation, and support policies that might result from life-cycle analysis [20]. High-level Air Force management must make it clear to these organizations that life-cycle analysis is here to stay. Contractors must be made equally aware of their role, and the credibility gap between the military services and contractors must be bridged. The military customer may have doubts about the contractor's ability or willingness to use valid life-cycle analysis in proposing new systems, especially if the results could affect follow-on sales the wrong way. The contractor must be convinced that the military is serious about wanting to emphasize qualities other than performance.

But such new relationships, new ways of looking at quality, new operational and maintenance practices—and, certainly, the new full use of life-cycle analysis—will not spring into being overnight.

If life-cycle analysis is to become a way of life in the military services, and if aspects of quality other than engine performance are to be considered, the services, the Department of Defense, and the highest levels of government must lend their continuous support in the form of both decisions and actions.

Appendix A

IMPORTANCE OF EARLY PLANNING FOR LIFE-CYCLE DECISIONMAKING

Many people in the defense community contend that almost all the important decisions defining and committing a weapon system to a total life-cycle capability and cost are made by the time the system is approved for full-scale production (DSARC III). For instance, Fig. A.1 shows the results of a Boeing study of their experience with several quite varied weapon systems. As indicated, 95 percent of the life-cycle cost has been defined upon arrival at the DSARC III milestone—almost the entire life-cycle cost at this relatively early point in time. This implies that a hardware design of inherent quality and expected capability has already been specified and developed to a certain state by this time, and all the accompanying decisions on a particular basing posture, mission profile, utilization of the fleet, logistics support, and manning and training—decisions that set the desired capability and resulting cost elements—have been made. Later decisions affect some marginal amounts of costs, such as those arising from product improvement programs, but commitment to the necessity for these improvement programs is really made earlier to the extent that the desired design is pushing the state of the art in the early development program. Clearly, one must continue the maturation of the weapon system after its introduction in the operational inventory, particularly if it has been hurried into operational use. Not all the problems can be solved in the development process, but there has to be some adequate measure of capability at Initial Operational Capability (IOC); consequently, there is a tradeoff between time and money spent in development to improve capability and reduce cost in operation and, particularly, the kind of testing employed to obtain this initial operational

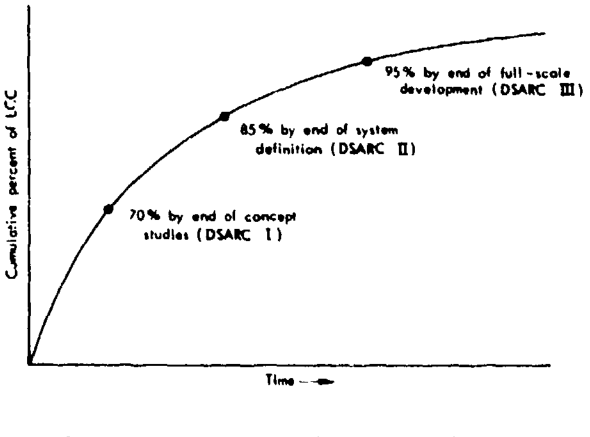

Fig. A.1—System decisions defining total life-cycle costs

Source: Adapted from E. H. Johnson, *Prediction and Estimating Methodology: The Key to Design to Cost* (excerpt), D180-19524-1, Design-to-Cost Laboratory, Research and Engineering Division, Boeing Aerospace Company, 1976, p. 7

capability. Of course, if the military waited until the new system was fully perfected, they might never get it or it would be obsolete by the time they did; the common solution is to accept a middle ground between inadequacy and perfection. Most of the impact of later decisions aimed at improvement in operational service seems to affect the capability side of the weapon system more than the cost side. A recent Rand study indicates that once the Air Force is fully committed to a particular weapon-system design and is implementing that program, the leverage is on improving capability rather than on reducing the cost.[1]

Does the engine life-cycle cost commitment look like the Boeing curve in Fig. A.1? The answer is unclear. Once the design requirements are set (i.e., for performance, durability, reliability, and maintainability), cost tradeoffs may be limited. By the nature of the acquisition strategy selected, a life-cycle cost commitment is being made even though the designer may not yet fully perceive its magnitude. Consequently, if decisions are already made, if development and production have been committed in a specific context to a constrained schedule, if endurance at the MQT has been accepted regardless of the impact on the weapon system and thus the CIP and modification costs are already assumed to be necessary to achieve a satisfactory level of reliability and durability, then this figure may obtain at the component level as well as at the weapon-system level.

Also, at the engine subsystem level, if reliability and durability improvements can be obtained from spending additional resources earlier and can then be translated into fewer periodic inspections at the base (and base manpower is reduced accordingly), and/or into significantly fewer trips to the depot for overhaul beyond what was expected in early planning, then the finding that improvements affect capability much more than cost may not be correct at the component level for engines. The leverage involved may differ for specific subsystem such as airframe and engine. This issue needs further research.

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[1] This has been seen in our current A-7D research within the Weapon-System Life-Cycle Analysis Project. This research seems to show that product improvement programs aimed at improving the reliability of an existing weapon system such as the A-7D affect capability much more than they do cost. The study indicates that doubling the MTBF of the weapon system results in a 60-percent improvement in availability of the system to fly a sortie, but only about a 6-percent reduction in cost. The message appears to be that, if one understands early in the conceptual phase what the potentials are for performance/schedule/cost tradeoffs, one can achieve some balance in terms of the most benefit achieved for the weapon system at the lowest life-cycle cost. See Refs. 21 and 22, and an unpublished Rand study by J. R. Gebman et al.

Appendix B

A NOTE ON DEFINITIONS AND DATA SYSTEMS

DEFINITION OF ENGINE

Within the tech order definition of a weapon system, the engine falls under work unit code 23, and the engine parts are described within the work unit code manual for the specific weapon system. However, among the various weapon systems in the Air Force inventory, there is no uniformity on what portions of the engine's related accessories fall within the 23 work unit code context, what portions become associated with airframe work unit code numbers, and what airframe accessories are assigned within the engine 23 work unit code number. Care must therefore be exercised in comparing certain data.

Concern is expressed here not only with the whole engine, but with the engine-related accessories (for instance, the main fuel control, the afterburner fuel control, fuel pumps, and gear box), and also airframe-related accessories that may be within the engine's work unit code structure. Airframe-related accessories are part of the QEC, or Quick Engine Change kit; such accessories include the starter and auxiliary power units, and in a number of cases for afterburning engines, the afterburner is assigned to the QEC. When an afterburning engine is removed from an airframe to be sent to the depot for overhaul, the afterburner and QEC are removed from the engine and only the dry engine configuration (including its accessories) is sent to the depot. The afterburner is considered part of the QEC, but is really an engine component that can be repaired in the field, and only in very special circumstances are afterburners for particular engines sent back to the depot for some special overhaul procedure. The propulsion shop can do the QEC repair as well as engine and engine accessory repair. QEC repair should not be charged against the engine. But when an engine is removed from the weapon system to be sent to a depot, then all the work of removing the QEC should be charged to the engine. Another problem with engine or airframe-assigned accessories is that they may be repaired at different air logistics centers, depending on whether they are defined as engine-related or airframe-related, and thus may be captured in a different cost accounting system. An additional problem at a given base arises if more than one type of engine is being repaired at that base, which is usually the case. Also, other shops supply labor to the engine shop for engine repair work. For these reasons, relating base maintenance cost to a specific engine is not a straightforward task. MDC 66-1 will give direct maintenance hours expended, but not maintenance available or parts costs. It is a difficult data problem, then, to measure exactly the overall effort chargeable to a specific engine's maintenance, and thus obtain base-level costs for engines in terms of labor and parts.

DATA SYSTEMS

The lesson one learns over and over again when trying to gain a life-cycle perspective of a weapon system is that a large number of data systems must be reviewed to obtain the pieces of data needed for assembling an overall picture of the life cycle. There is presently a lack of certain data in the particular form needed for analysis, especially ownership data. There is in addition the problem of inconsistency of data sources— two data systems that disagree although both supposedly obtain the same data from the same basic source. Part of the problem may be that the two sources do not exactly cover the same time period; perhaps one of the sources requires more reporting approvals and needs more time to get the data through channels than does the other. Another reason may be that all the available data, overseas as well as CONUS, may be in one system and not in another; the user may be confused unless that scope is clearly stated.

The type of data most readily available for this study were aggregated, heterogeneous, and cross-sectional in nature; that is, gross, weapon-system level cost totals for several fiscal years that may not be internally consistent across those years. Life-cycle analysis requires disaggregated, homogeneous, longitudinal data, cost data broken down below weapon-system level into specific consistently defined categories, available over a considerable period of time, such as ten years. Nowhere in the USAF have ownership cost data been preserved for such a period; the general practice is to save cost data for about three to four years.[1]

For engines, the best source of RDT&E/CIP and procurement data is the contractor, since he is in the best position to break out the detailed cost elements for each portion of the various costs associated with a particular contract, and he does save these cost data for many years. These data are valuable to him for analysis of new engine programs, whereas the military services, because specific contracts may cover a multitude of items procured by a lump-sum cost, are hard-pressed to attempt a detailed breakout of costs long after the fact. For instance, a given Air Force contract may include not only the procurement of whole engines, but some allotment to spare parts, management data, field support, and so forth.

The best data source at present for depot costs appears to be the H036B data system, which Hq AFLC uses to forward to DoD its depot repair costs for aerospace equipment.[2] An additional source of depot cost data is the DPEM account obtained from the comptroller at AFLC (G072 data system). The G019 MISTR data (Management of Items Subject to Repair) are also valuable. MISTR items concern the repair of reparable parts for engine overhaul and also for field support of those items. Under the current AFLC Plan 72-10, certain MISTR costs are now apportioned to the whole engine depot overhaul cost, so that H036B would appear to capture an estimate of the full cost of overhauling a whole engine. MISTR also would have the detailed costs concerning field support of reparable parts. What is needed at the depot level is not only the whole engine overhaul cost, but also costs for engines

[1] This is perhaps going to change in the near future; several data systems forthcoming at OSD and Hq USAF apparently will preserve costs over a longer period. VAMOSC (Visibility and Management of Operating and Support Costs, OSD/I&L) and OSCR (Operating and Support Cost Reporting, AFAC) are now being implemented. It is to be hoped that similar systems will also provide the kind of data needed at the subsystem/component level.

[2] See DoDI 7220.29. Data as of 1974 reflect the new system and are of higher quality. Earlier data are suspect.

repaired but not overhauled, MISTR costs associated with repair of reparable parts from the field that are then returned to the field, the costs of modification parts, and the recurring investment cost of reparables that are added to stock when other reparables are condemned. Expendable parts, accounted for by the stock fund, are included in the fully burdened depot labor charge against overhaul and repair of engine and exchangeables. All these different costs must be included in an analysis of depot costs.

To obtain cost elements at the base, the Resource Management System, which uses the 1050 computer, is useful for costs associated with specific base cost centers. This system will provide the cost associated with operating the engine shop, for instance. The difficulty in obtaining engine-related base costs is that a single base may take care of two or more engine types, and the engine shop is not the only source of labor related to engines. Costs associated with the engine shop involve work on all engine types at a base, and costs are not separated by weapon system. Another data source for manpower expenditure, direct labor expended at the base to fix specific hardware, is the 66-1 MDC data. These data detail the direct manpower expended to maintain the weapon system, and it is possible to extract the work unit codes associated with scheduled and unscheduled engine maintenance. But even here, there are problems. Knowing the man-hours consumed from 66-1 does not give the full cost of manpower in the engine shop. Utilized manpower is not the same as available manpower. One way to obtain the full manpower cost is to refer to the Unit Detail Listing (UDL) to determine the number of people in the engine shop. The UDL headcount of an engine shop would then reflect the major share of the cost of base maintenance for all propulsion on that base. It would not, however, reflect the total costs. As previously noted, specialists are often borrowed from other shops to perform work on engines; there are other support areas such as Nondestructive Inspection (NDI) that are almost totally monopolized by the engine shop; and there is the maintenance effort associated with the ground support equipment needed to support engine maintenance.

Regarding spare parts, the engine manager at the depot is perhaps the best source of data, particularly for the reparable parts. He has some expendable parts costs, but he may not have them all. Depot supply and base supply may have to be checked to determine what portion of expendable parts is being consumed outside the engine manager's cost accounting system. One of the engine spare parts programs is the D041 at the depot. In addition, engine-related systems information, such as D024 for engine data and D056 for weapon-system data, are useful in providing certain information on engine overhaul times, maintenance man-hours expended per flying hour, MTBFs, etc.

There have been attempts at bringing all the operating and support maintenance data together. One example is the AFLC data system called Increased Reliability of Operational Systems (IROS), which is intended to bring together maintenance labor and parts costs associated with the depot and the base for a given weapon system by work-unit code. IROS could not be used for this study since one of its major problem areas is with engines.[3] It should be emphasized that a data system such as IROS could be extremely valuable for life-cycle cost tracking.

[3] See M. R. Fiorello and P. Konoske-Dey, *An Appraisal of Logistic Support Costs Used in the Air Force IROS Program*, The Rand Corporation, R-1569-PR, February 1975. Suggestions are presented in the report for improving IROS usefulness.

Appendix C

DEPOT MAINTENANCE ACTIVITY

The primary function of the USAF engine depot is to overhaul engines and accessories to restore them to what is termed a "zero-time" status, allowing the overhauled hardware to be flown again to the maximum time allowed by maintenance policy decisions. Besides this primary function, several other engine-related repair activities go on at a depot. They include immediate correction of hardware deficiencies that are causing safety-of-flight problems and could result in grounding of the fleet; minor repairs of engines that do not need major repairs; modifications to engines to replace parts that have been obsoleted for deficiency or reliability reasons; repair of reparable parts and accessories; and replacement of reparable parts and accessories that are condemned. To understand the true cost of operating a depot, all of these activities and their related cost elements must be identified and accumulated.

The basic engine maintenance philosophy in the Air Force might be termed "hard time" in the sense that certain maintenance actions are required in the field and at the depot when a specific number of flying hours has accumulated for a certain engine model on a particular aircraft, regardless of how well the engine is operating in the field. For instance, the J79 engine must have a periodic inspection at an operating base at about 600 flying hours, regardless of how well the engine is working on the aircraft. (At a minimum, the combustion liners must be replaced at that time.) For that purpose, the engine must be removed and disassembled and a spare engine installed on the aircraft. It takes two days to remove and replace a J79 engine on an F-4 aircraft, and it can take up to several weeks to complete the periodic inspection. Later on, the engine must go to the depot at 1200 hours for a zero-time overhaul, regardless of how well it is operating. These times are not rigidly fixed; there is an allowable margin of plus or minus 10 percent.

DEPOT COSTS

The major depot cost is considered to be the cost associated with "zero-timing" an engine. In this process, the engine is completely disassembled and the parts go off in various directions to be reworked, modified, or condemned and replaced by new parts. Then, as the "engine nameplate" moves down the depot floor, these or similar parts come together again until, at the end of the line, the engine is completely reassembled and is considered to be a zero-time engine; that is, it is capable of operating for the full MTBO interval ending with its next trip to the depot. Most of the parts now in the engine probably were *not* in the engine when it arrived at the depot.

The cost associated with whole-engine overhaul is the cost of labor and parts, including the labor for whatever modifications are incorporated into the engine while it is in the depot. The modification kit parts cost is not included; it is a separate account provided as a "free good" to the depot or base, wherever the modification is being accomplished. The cost of these kits may be in either the BP1100 or BP1500 account, depending upon whether the modification is a forced change (must be done quickly) or can be accomplished at the next zero-time overhaul. All of the parts, labor, and overhead, except modification parts for an engine overhaul, are considered to be within the H036B cost accounting system, which is the principal source of depot overhaul costs for this study.[1] Other sources of cost data have also been investigated and will be compared to the H036B cost.

Apart from whole engine zero-time overhaul, some engines require urgent modifications at the depot during their operational use in the field. This occurs, for instance, when a major design defect has been uncovered, as when a defect in the first-stage turbine of the TF41 engine grounded the A-7D fleet. The problem had been deemed critical to safety of flight and therefore had to be corrected before the aircraft could be restored to flying status. Such modifications are non-zero-time modifications because the rest of the engine is usually left alone. Other critical modifications may be added to the work package, however, and incorporated conveniently into the engine at the same time. Data on these activities are also part of the H036B system.

In addition to these two costs, a considerable depot cost is associated with the repair of parts and accessories of a particular engine that go through the MISTR line (Management of Items Subject to Repair), but that are not incorporate into a whole engine overhaul. These are parts that come in from a base for repair, go through the MISTR line, and then go back to the base. These repair costs must also be considered in the engine life-cycle cost. In addition to MISTR, which is confined to component repair (e.g., a compressor rotor), are the associated 72-10 costs for repair of all parts not considered components.

Table C.1 lists man-hour forecasts for work related to engine overhaul and MISTR field support for six engine programs, furnished by the Oklahoma City Air Logistics Center. The estimates are for a planned FY 1976 workload. These are planning figures, not actual data from previous years. There appears to be an enormous difficulty in obtaining actual costs from previous years for MISTR field support. It requires a large manual effort at the depot to separate MISTR field-support charges from overhaul charges for a given engine program. Such historical data were not available for this study; consequently, to proceed with the task of trend-analysis, the estimates for FY 1976 have been used as a rough approximation to obtain the additional effort required at the depot beyond overhaul cost to support the repair of exchangeables from the field. Actual costs must be verified later to determine the accuracy of that portion of the analysis. From the ratios in Table C.1, it can be seen that the MISTR field support is a very significant portion of depot activity and must be considered in estimating the cost associated with depot repair for engines. Total lack of data in the MISTR area over time precludes answering, in this study, interesting policy questions concerning the effect of JEIM return rates, cost to the depot of field support, and the effect of designing an engine for field maintenance.

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[1] This accounting system was initiated by DoD Instruction 7220.29, *Uniform Depot Maintenance Cost Accounting and Production Reporting System*, October 28, 1968, which was later amended in October 1975. The new edition will now provide the guidance in accounting for and reporting the costs of depot maintenance and maintenance support. Because the first year covered by the Handbook will be FY 1977, data from the new system will not be available until 1978

Table C.1

Engine	Engine Overhaul Man-hours	Engine Field Support Man-hours	Total Depot Man-hours	Engine Overhaul/ Total Depot
J57	650,628	487,028	1,137,656	0.57
J75	237,150	109,979	347,129	0.68
J79[a]	365,721	76,587	442,308	0.82
TF30	786,325	277,986	1,064,311	0.74
TF33	445,666	130,885	576,551	0.77
TF41	686,430	76,070	762,410	0.90

[a] Incomplete.

Finally, there are the material purchases. Of concern are the modification parts mentioned (BP1100) and expendable (SSSF) and exchangeable materials (BP1500). All expendable materials costs related to a particular engine may not enter the engine manager's cost accounting system within the Support System Stock Fund (SSSF), but may be in the depot supply system or base supply system because of direct purchases by these supply organizations from the prime organization responsible for those particular parts, which may not be the Air Force. The prime could be the Army, the Navy, the Air Force, or the Defense Supply Agency. Table C.2 presents cost data on expendable materials for three fiscal years. The costs are for families of engines, not broken down by application. The costs are significant and can vary widely from year to year, depending on funds available, problems with engines, and parts defined as expendable in any given year. A charge is levied in the "loaded" labor rate for a particular engine at the depot to account for expendable materials used in overhaul or reparable repair. Table C.3 presents current labor rates for selected engines at Oklahoma City Air Logistics Center. Note the substantial charge against materials that are of the SSSF expendable type. One problem is whether this cost by family fully charges engines on the basis of their application. An assumption in this study is that the depot is capturing the major portion of SSSF costs for parts consumed in the depot and/or shipped to a base, and that the base is adequately capturing its share. Thus, parts that might be lost in accounting have a negligible effect on total cost. A problem with previous studies has been the use of labor rates of about $10 to $15 per hour when calculating depot labor costs. Table C.3 shows a range of roughly $25 to $40 per hour. Without the expendable materials, labor rates are still $18 to $24 per hour.

Also of concern is the cost of the modification kits, parts that are not included in the overhaul costs. There is a BP1100 account, but because engine costs are not separated from the total weapon-system cost in this account, BP1100 costs do not appear to be available that can be directly related to at least an engine family. This should be attempted in the future. Presently, to obtain such costs, it would be necessary, for a given engine family, to go back over the entire history of that engine in order to gather together all of the engineering changes that occurred during its lifetime. That would be an enormous undertaking at this time. In the future, it would be valuable to maintain such records separately and keep accumulating them over time for a new engine. These ECP costs should originate at the beginning with the SPO and continue on through the engine manager at the

Table C.2

EXPENDABLE MATERIAL COSTS, SSSF
(In millions of 1975 dollars)

Engine	FY 73	FY 74	FY 75	Average
J57	28.21	18.95	14.31	20.49
J75	5.61	5.97	3.72	5.10
J79	21.07	20.99	24.37	22.14
TF30	7.21	9.20	14.15	10.19
TF33	4.72	7.35	5.45	5.84
TF41	13.40	7.94	23.09	14.81
Total	80.22	70.40	85.09	78.57

Table C.3

LABOR RATES
(In 1975 dollars)

Item	J57	J75	J79	TF30	TF33	TF41
Labor	9.234	9.293	9.110	9.234	9.538	8.436
Material	6.060	6.942	6.006	15.828	9.284	14.204
Other	13.210	14.186	11.791	13.191	13.366	10.590
Total	28.504	30.421	26.907	38.253	32.183	32.230

depot when the transition of the engine from AFSC to AFLC occurs, thus maintaining a total time track of modifications to the engine throughout its history.

Reparable parts purchases required to replaced condemned variables at the depot should be fully captured by the engine manager (in what is called the BP1500 account). These costs, at least by engine family, are available and must be considered an additional charge against the total maintenance cost at the depot for an engine. Table C.4 presents three years of data for selected engine families. Again, the costs can vary widely from year to year and they cannot be tracked to specific applications. The wide variation can depend on problems related to engines, funding availability, and the use of these funds in purchasing new parts. They are sometimes used for BP1100-type purchases if the modification is not "forced" to the depot immediately or if parts are second-time purchases, not initial purchases.

DEPOT REPAIR COSTS

The primary measure of benefit used in this study is the engine flying hour. In examining an engine life cycle, there are two views of this benefit for estimating costs at the depot: the flying hours consumed by the operating fleet and the flying hours restored to the fleet by zero-timing at the depot. Under steady-state conditions, it is to be expected that demand equals supply and that consumed flying hours (demanded by the user) would approximate restored flying hours (supplied to the user from the depot). This can be seen from the data in Table C.5.

Table C.4

COST OF REPLACING CONDEMNED REPARABLES, BP1500 FUNDS
(In millions of 1975 dollars)

Engine	FY 73	FY 74	FY 75	Average
J57	61.36	22.93	41.84	42.02
J75	2.64	1.91	10.50	5.02
J79	16.78	9.50	11.61	12.63
TF30	26.08	25.31	27.38	26.26
TF33	18.53	6.96	10.17	11.89
TF41	10.36	13.30	11.80	11.82
Total	135.75	79.91	113.30	109.66

Table C.5

FLEET ENGINE FLYING-HOURS CONSUMED AND RESTORED AT THE DEPOT, FY 1974

Engine	Aircraft	Fleet Engine Flying hr Consumed	No. of Engines Overhauled	Average Time to Overhaul	Engine Flying hr Restored	Ratio Flying hr Restored/ Consumed
J57-P-19/29	B-52D	375,936	113	3,666	414,258	1.1
J57-P-21	F-100	91,383	167	752	125,584	1.37
J57-P-43	KC-135	801,715	358	3,273	1,171,734	1.46
J75-P-17	F-106	59,527	77	874	67,298	1.13
J79-GE-15	F-4C/D	577,821	452	948	428,496	0.74
J79-GE-17	F-4E	307,141	265	1,057	280,105	0.91
TF30-P-3	F-111	100,452	137	556	76,172	0.76
TF30-P-100	F-111	37,946	18	374	6,732	0.18
TF33-P-3	B-52H	296,009	101	2,880	290,880	0.98
TF33-P-7/7A	C-141	1,242,214	207	6,934	1,435,338	1.16
TF39-GE-1/1A	C-5	189,336	113	1,200	135,600	0.72
TF41-A-1	A-7D	111,405	115	333	38,295	0.34

DEPOT REPAIR COSTS SUMMARIZED

The full cost of engine depot repair activity is the sum of the costs associated with zero-timing, the repair line, field MISTR support, modification kits, and the replacement of condemned reparables. It was not possible during this study to obtain costs associated with modification kits (the BP1100 money) because the funds were not broken down below weapon-system level. These costs must be obtained in the future to improve the perspective on total depot costs. Two separate data sources were compared in arriving at depot repair costs: (1) the H036B repair cost, MISTR estimate, and BP1500 cost, and (2) the DPEM account and BP1500. (Total DPEM is supposed to contain all MISTR costs.) The two sources (H036B and DPEM) indicate different costs and flying hours. Thus, a range of costs and flying hours is obtained for the depot repair activity, as shown in Table C.6. Table C.7 presents the results of comparing the H036B and DPEM data, showing costs estimated for both flying hours consumed and flying hours restored. For the mature engines, the costs fall within a reasonably narrow range, thus describing a fairly steady-state situation, whereas for some of the engines that are in their earlier phase of life cycle and not as mature (i.e., the TF30, TF39, TF41), the cost comparison between consumed and restored hours shows a wider range. There is some difference among the various engines when the two data sources are compared. It is interesting to note that dollar totals for all engine activities vary by less than 7 percent between the two data sources and estimates (See Table C.6).

Table C.6

COST DATA COMPARISON
(In millions of 1975 dollars)

Engine	HO36B (reported)	MISTR & MODS (est.)	Total Cost	Engine Flying Hours (DO24)	DPEM Costs (reported) Engines	Engine Access.	Total Cost	Engine Flying Hours (DPEM)
J57-P-19/29	5.6	4.2	9.8	375,936	3.59	8.13	11.72	284,032
-21	9.6	7.2	16.8	91,383	5.04	1.97	7.01	85,921
-43	20.3	15.2	35.5	801,715	17.89	13.41	31.30	868,632
J75-P-17	5.6	2.6	8.2	59,527	1.86	6.20	8.06	60,089
J79-GE-15	26.6	5.6	32.2	577,821	15.29	20.97	36.26	838,342
-17	12.3	2.6	14.9	307,141	—	—	—	—
TF30-P-3	10.0	4.3	14.3	190,452	6.18	8.91	15.09	160,668
P-100	3.0	2.0	5.0	37,946	—	—	—	—
TF33-P-3	6.4	1.9	8.3	296,009	1.92	5.37	7.29	266,296
P-7/7A	14.7	4.3	19.0	1,242,214	3.72	31.85	35.57	1,162,764
TF39-GE-1/1A	19.7	2.0	21.7	189,336	3.28	14.62	17.90	177,380
TF41-A-1	8.3	5.5	13.8	111,405	10.95	4.75	15.70	78,071

Table C.7

DEPOT COST PER FLYING HOUR

Engine	HO36B Totals $/EFHC	HO36B Totals $/EFHR	DPEM Totals $/EFHC	DPEM Totals $/EFHR
JP57-P-19/29	36	35	51	38
J57-P-21	194	165	92	66
J57-P-43	54	46	46	37
J75-P-17	157	146	153	139
J79-GE-15	67	83	(a) 54	62
J79-GE-17	60	64		
TF30-P-3	265	296	(a) 217	405
TF30-P-100	255	622		
TF33-P-3	32	32	31	29
TF33-P-7/7A	19	17	35	29
TF39-GE-1/1A	125	166	111	142
TF41-A-1	243	385	320	529

[a] DPEM data are for a combined weapon system (e.g., all F-4 aircraft) and cannot be separated by engine dash numbers.

Appendix D

BASE COSTS

The engine costs at the base are related to maintenance labor, parts, and support for the following activities: unscheduled maintenance in the shop, including removal and replacement of engines and accessories; periodic scheduled maintenance (including base-installed modifications); engine test checkout before reinstallation; and removal and replacement when an engine is to be returned to the depot. Judging from 66-1 MDC and D056 data, it appears that from one-half to two maintenance man-hours per flying hour are required for maintenance labor on the engines of a variety of weapon systems in the Air Force inventory. In using the 66-1 data, however, one must be careful to include all engine-related work—the scheduled as well as the unscheduled maintenance. Also the data from 66-1 represent labor utilized. When engine shop personnel available are counted, the maintenance labor available is on the order of one-half to two maintenance man-years per possessed engine on the base; this can translate to from three to six maintenance man-hours per flying hour, depending upon the particular weapon system and its flying hour program.

Available manpower is what the Air Force is paying for in terms of the total maintenance labor cost. The Air Force has a policy on the necessary manning for a wartime contingency, and pays for that level even if it is not fully utilized in peacetime.

There are additional considerations in attempting to understand the maintenance workload for a particular engine. Maintenance labor associated with other shops is used for engine-related work. Included in this category would be Nondestructive Inspection (NDI), for which specialists are drawn occasionally from other shops such as welding, fabrication, or electrical, and the maintenance associated with peculiar and common aerospace ground support equipment required to support the engine. These considerations would add to engine-related labor. On the other hand, other considerations might cause engine labor to appear larger than it really is. Because the one propulsion shop at a base handles all engines present at the base and does not keep separate records by engine type, it is difficult to sort out engine-specific maintenance data (unless, of course, only one engine type is present at the base). Also, it appears that one-fourth to one-third of base engine shop labor may be expended on Quick Engine Change (QEC) items. QEC items are airframe-related accessories that are mounted on the engine for convenience in removing and replacing the engine. A problem for the analyst with QEC labor is to determine whether an airframe accessory had to be removed to get at the engine or whether there was a problem with the accessory itself. It is difficult to do so with existing data.

Concerning parts costs at a base, the same kind of data problems arise as encountered at the depot. Reparables appear to be accounted for, since they do flow through the depot, the cost of repair is captured there, and reparables are condemned at the depot. When they are repaired at the depot, costs for labor and parts are captured in the H036B system if included in a zero-time engine overhaul, or are in the field support MISTR or 72-10 accounts if a component or part is returned directly from the field. The overhaul of an engine is charged with 20 percent of the current list price of the reparable part (based on latest purchase price, which could be several years old) when such a removed reparable is exchanged for a repaired reparable. Condemnation costs for replacing reparables are supposed to be in the 20 percent factor but are not adequately covered there. Their cost is captured by the BP1500 investment account. The difficulty comes in fully accounting for the expendable-parts consumption related to engine repair at the base: identifying what is supplied from a depot and what the base buys directly offbase from whoever may be the prime agency for a particular stock number (which could be the Navy or Defense Supply Agency rather than the Air Force). Thus, supply cost can be found within the RMS system for a particular cost center like the engine shop. But that total cost (which includes consumables, expendable parts, and other general supply items) will be the total cost for supporting all of the engines at the base, and breaking it out in terms of a particular engine may be difficult. How are these costs to be apportioned for the various engines at a base?

An additional cost area is the base operating support: supply, wing overhead, clerks, technicians, military police, civil engineers, hospital, and transportation people, and materials they all use, are not within the engine shop but are required on the base to support engine-shop personnel and engine work. These also represent an additional cost. To the extent that training at the base is represented by OJT (On the Job Training), this cost is picked up by the headcount of the propulsion shop. Off-base training is not considered here.

There appears to be no single integrated data source for all costs related to engine maintenance at a base. This study has used data from a variety of sources to estimate the base labor and parts costs for selected engines in the Air Force inventory.

At present, it appears that one way to estimate the base cost of maintenance labor for an engine is to examine the UDL. Available labor is what the Air Force is paying for. The data from several selected bases indicate that maintenance labor will vary from one-half to two maintenance man-years per possessed engine, depending on the particular engine. Some administrative and support costs must be added to this direct labor cost (a 50-percent add-on is assumed here). Thus, one maintenance man-year is estimated to cost $10,000 in direct labor and an additional $5,000 in indirect costs, for a total of $15,000. Expendable parts must be estimated (a range of from more than $1,000 to less than $5,000 per engine per year is possible for first-line engines depending on the engine)[1] from an examination of BMS, depot supply, and engine manager accounts. This total base cost may not be as large as depot costs for most engines, but is still significant.

An effort was made to relate base costs obtained from estimates of propulsion shop manning and supply expense to parameters of interest in order to obtain a base cost-estimating relationship. The range of costs obtained are shown in Table 3.20. The maintenance man-years per possessed engine ranged from one-half to one for most engines in the inventory. Supply expense varied as shown in the table. An average value was then used in generating cost-estimating relationships. The specific data are presented in Table 3.21. The results in Table 3.22 are interesting in indicating explanatory variables, but the model, due to the nature and limitations of the data, should be viewed cautiously. For base maintenance costs, MTBO (the policy-determined maximum time between depot overhaul) was most significant, entering the relationship negatively. Thus, efforts to extend MTBO would reduce base costs, since periodic scheduled inspections are directly related to MTBO and are a significant portion of propulsion shop activity. OPSPAN entered positively; the longer an engine is in operational service, the more costly it is to maintain at the base. CPUSP entered positively; the more expensive the engine, the more it costs to maintain at the base. It therefore appears that efforts to increase MTBO (through on-condition maintenance using engine health monitoring or diagnostics systems) and decrease the engine purchase price could work toward lowering base maintenance cost. As discussed previously, production learning and state-of-the-art effects could be considered to be included indirectly through CPUSP. Again, it must be emphasized that this model represents only the grossest cost estimate for the base. An improved model must await better data from new or improved base data-collection systems and detailed examination of base-level data.

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[1] For instance, the J79-GE-17 on the F-4E at Seymour Johnson AFB, North Carolina, requires about two-thirds maintenance man-year per possessed engine on the base, and supply accounts indicate about $1500 per engine per year in expenditures for FY 1975.

Appendix E

SPARE ENGINES AND OTHER COSTS

Spare engines add approximately 25 to 50 percent to the installed engine inventory in the Air Force. Table 3.23 presents a list of installed and spare engines for selected systems. These engines account for at least 20 percent of the total procurement cost of engines for a weapon system. They also have the effect of diluting the number of expected flying hours per engine over the life cycle. Thus, an engine designed and purchased with the expectation of operating for 5000 flying hours within a specified time period will probably fly only around 4000 hours during this period, on the average, if the engine has a 25 percent spares ratio. The spares ratio appears to be application-oriented in that, as can be noted from Table 3.23, the lower percentages appear to apply primarily to subsonic transport and bomber aircraft while the higher percentages pertain more to supersonic applications. The cost of spare engines can be handled directly when computing the total cost for a quantity of engines procured during a weapon system's lifetime, as discussed in a previous section of this report. Spare engines bought during the same period as the installed engines should have the same progress slope applied, and indeed, should help in reducing the cost of future engines. The spares merely add to the quantity of installed engines to be bought. But how many spare engines do you buy?

There is a specific computation to obtain the number of spare engines required for a weapon system.[1] On the basis of factors such as programmed flying hours, number of installed engines on the aircraft, number and location of operating bases, and where certain repairs of the engine are to be made, a requirement is established for a specific number of spare engines at a given base and the engines required to fill the pipeline between the base and the depot. Specific numbers of days are estimated for the time it will take a base to turn an engine around at a base and a depot to process an engine at overhaul. The spare engines serve as replacements for failed engines that are removed for repair. A fill-rate objective is specified in terms of the ability to meet the demand for a spare engine. If the demand cannot be met, it is called a back order, which is defined as an aircraft requiring an engine. With the fill rate and a certain number of spares at a base, an expected effectiveness rate can be calculated—that is, the rate at which aircraft have their spare engine requirements satisfied and again become operational. A confidence level is also associated with this process. For combat aircraft, the confidence level is required to be 90 percent. Spare engine requirements are estimated on the basis of the minimum quantity of engines essential to support the programmed peacetime or wartime engine operation, whichever is greater. Since wartime flying is usually programmed at a higher rate, it is to be assumed that the spares are applicable to the wartime posture. Thus, spare engines are intended to reflect wartime requirments in terms of a fill-rate objective and effectiveness rate at some confidence level. Usually, more spare engines are purchased early in a new weapon-system program, and then phased down to the computed requirement as experience is gained. But the computed wartime requirement could still be higher than is necessary, particularly if appropriate consideration is given to attrition and duration of the conflict.

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[1] The standard computation procedure is DoDI 4230.4, *Standard Method for Commputation of Spare Aircraft Engine Procurement Requirements*. The Systems and Resources Management Advisory Group also studied the spare engine situation and recommended reexamination of spare engine procurement with the idea that the Air Force might be able to reduce spare engine procurement without degrading combat support capability.

Current planning estimates by which spares are computed indicate that engines should be turned around at a base in about 7 to 10 days and overhauled in about 30 to 40 days; but current experience indicates that it takes anywhere from 2 to 21 days to turn an engine around at a base, and anywhere from 27 to 114 days to process an engine through overhaul. Data are shown in Table E.1 for selected engines going through overhaul during FY 1975. The basic reasons for the large delay times are lack of parts and the requirement to retest engines that were not able to pass a check run at the end of the overhaul process. The additional delays these engines encountered at the depot, where some engines took two to three

Table E.1

DEPOT FLOW TIME, FY 1975

Engine	Standard Days	Actual Days	Cause of Delay	% Delays Due to Cause
J57-19	38	114	rejects	82
-21	38	70	rejects	72
-23	38	—		
-29	38	94	rejects	71
-43	38	44		
-55	60	68		
-57	35/45	—		
J75-17	40	90	parts	50
-19	40	89	parts	89
-19W	40	73	parts	89
J79-11	60	—		
-15/15A	32	29		
	32	32		
-17/17A OC	32	57	parts	66
SA	32	27		
TF30-P-3	35	92	parts	73
-P-7	35	66	parts	82
-P-9	35	33		
-P-100	35	66	parts	82
TF33-P-3	40	—		
-P-5	40	—		
-P-7A	40	49	parts; rejects	35 49
-P-9	40	—		
-P-100	40	87	parts	88
TF39-GE-1/1A	40	55		
TF41-A-1	36	46	parts	76
-A-2	36	52	parts	68

times the standard, suggest that more spare engines would be required in the system in order that engines be available at bases for the weapon system to maintain its operational status. For these engines, delays were evidently tolerated by the users, who were evidently still meeting peacetime flying requirements for the most part. It could be concluded, then, that a wartime spares posture in peacetime operation allows considerable slack in the system, permitting the system to relax and perhaps even to buy fewer spare parts if there is a budget problem.[4] The original wartime spare engine requirement evidently maintains the system in a spares-rich situation in peacetime. Thus, an analysis of spare engine requirements must deal with a wartime scenario as well as peacetime flying, not only on the basis of the flying hour program, but also on the ability of the support system to respond by providing engines in time periods considered more reasonably close to the standard. In a wartime situation, the question is whether the depot can provide engines within the 30-day standard used for computation. A further question is whether, in a wartime scenario, the effect of attrition will tend to lower the number of spare engines required.[5]

There would appear to be a tradeoff between whole spare engines and spare parts stockage necessary at base and depot to minimize cost and time delays for maintenance performed. One problem is that many support decisions are made early in the development of a new engine, prior to flight testing and operational use. Paper estimates are used in determining some of these support requirements. When flight testing and operational use indicate different problems, i.e., different failure modes for this particular engine as opposed to similar engines of the past, it is by this time very difficult and expensive to change the support posture. An additional cost, or lack of benefit, is the time an engine is out of commission for repairs and requires a spare engine to replace it in the weapon system. If this out-of-commission rate could be reduced, spare engine requirements could be reduced and, perhaps even more important, the availability of the weapon system could be increased. And if an engine could be turned around faster at a base or through the depot pipeline, spare engine requirements could be reduced. The depot repair cycle is the longest period of time that an engine would be expected to be out of commission.

This area of spare engine requirements appears to be fruitful for research. What is the real requirement for wartime spares? How many engines are required and what level of protection do these engines furnish if attrition is considered? What actions can be taken in a wartime contingency to alleviate any shortage in the early days—for instance, in the short term extending periodics and delaying MTBO removals, while in the long term procuring more parts and spare engines and allowing work force overtime at the base and depot? The NRTS policy (Not Reparable This Station) should also be examined critically in the early stages of engine design. The NRTS policy is basically an agreement between the base and the depot concerning the level of repair activity each will accomplish for a particular engine program. In some instances, this policy can work counter to the productive, efficient use of engines. For instance, if a base is short of a part and is not going to get it for some time, the base may simply decide to ship the engine to the depot in exchange for a refurbished engine, even though the depot may also be short of that part. In that case, the engine will have to sit at the depot, and when it does get the part, it may then have to go through overhaul earlier than if it had not been shipped from the base.

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[4] Note the fluctuation in SSSF and BP1500 funds for these engine families, presented in App. C.

[5] A current study in Rand's logistics program suggests that it will. A dynamic transition and wartime scenario provided different results from those in an assumed steady-state situation.

Commercial data indicate that the airlines use fewer spares—on the order of half the spares that the military use for a comparable application. Table E.2 presents selected commercial data taken from Ref. 8. Data also indicate that the airlines process their engines through the shop much faster. The airlines know they are tying up valuable assets when their engines are going through the shop, and therefore make every attempt to get them out within 15 to 30 days. In fact, for the high-bypass engines, they strive for a two-week turnaround. The modular design of these engines speeds up the process, because work can often be confined to only those modules needing repair.

Table E.2

COMMERCIAL JET ENGINE INVENTORY

	All Airlines	United	American	TWA
Installs	7734	1203	823	901
Spares	1044	153	120	99
Total	8778	1356	943	1000

SOURCES: For all airlines: installs from *Certified Route and Supplemental Air Carrier Fleet Inventory on June 30, 1975*, CAB, September 12, 1975; spares estimated at 13.5% based on composite of United and American actuals. United Airlines, *Aircraft and Engine Inventory as of August 22, 1975*; includes 56 installs from two other airlines as per pool arrangement. American Airlines, *Aircraft and Engine Inventory as of August 1, 1975*. For TWA, installs: CAB report cited above; spares: TWA estimate for engines and modules as of July 11, 1975.

Table is taken directly from Ref. 8.

In the case of military engines, which are currently taking two to four times longer than expected, either more spare engines must be in the pipeline (the situation is spares-rich for peacetime operation) or aircraft must be down because of the lack of engines (which does not seem to occur). In either situation, the weapon system incurs an additional cost related to the additional pipeline time. A question the logistics planner may wish to consider in that situation is whether it would be beneficial to buy more spare parts that are in short supply to reduce the pipeline time, thus not requiring as many spare engines and not having aircraft down for the lack of an engine. (To estimate the cost of aircraft downtime, one approach would be to take the total life-cycle cost for a weapon system and divide by the total number of days the system will be operational in its life cycle.)

As a possible way to speed the pipeline, the Air Force should review the decision rules applicable to testing engines at the depot to affirm that they meet original specifications. Perhaps the specs could be relaxed for older engines that have been completely overhauled. The risk is these engines may end up being returned to the depot with fewer flying hours accumulated at their next visit. That risk would have to be weighed against the cost of delay, the cost of spare engines, and the cost of aircraft downtime. Another possibility is to design more temperature margin into the engine during development. MIL-5007D appears to be heading in that direction.

Spare parts shortages may be due to several possibilities: (1) The engine is less reliable than anticipated, and not enough spare parts were procured. (2) Budget constraints forced a reduction in spare parts procurement for a given year. (See BP1500 funding for three recent fiscal years. In FY 1974 it was considerably lower than in FY 1973 or FY 1975.) (3) Spare parts may be plentiful at the depot, but they are not the right ones because a particular component has been modified and the depot is waiting for the modified parts. This is another reason for trying to determine as many engine reliability problems as early in the life cycle as possible so that the initial operational reliability is high, the entire inventory does not have to be modified because of a severe problem, and large quantities of parts procured earlier do not become obsolete.

The new modular design engines, such as the F100 on the F-15 and the F101 on the B-1, are intended to significantly reduce the requirement for whole spare engines. The objective here is to be able to "swap out" modules in the field and repair them at the base or depot; thus spare modules are required, but not entire spare engines. This should help to reduce the cost of the inventory, if indeed this practice is accomplished and "swapping out" turns out to be a reasonable thing to do. As yet, the military has little experience with this procedure, but there is some commercial experience indicating that it is valid. TWA does "swap out" modules for the RB-211 engine on the L-1011 aircraft at their maintenance base in Los Angeles rather than at their main facility in Kansas City.

In summary, the military apparently requires 25 to 50 percent spare engines in their inventory; the commercial airlines appear to make do with fewer spares for a comparable application. Part of the reason for this has to do with the depot pipeline repair time previously discussed: Airlines try to turn comparable engines around within 15 to 30 days. The Air Force is currently having difficulty turning engines around in 45 to 90 days. Besides the pipeline time and the additional spares needed for the pipeline, there is a requirement that there be additional spares at each Air Force base (from 6 to 12 spare engines are usually at an operating base). The airlines also must maintain spares at bases, but their stockage policy appears to be much lower. The wartime scenario computation requirement appears to be the driving factor resulting in a large spare engine inventory for the Air Force. This area appears to be a fruitful one for future research.

The cost of spare engines is really an ownership cost. They are needed to support the users' flying program. They should be identified separately in any life-cycle cost pie. For early planning purposes, the cost can be most readily obtained by calculating the cost of total procurement of all engines for a given program and then separating the installed and spares costs in proportion to the number of units purchased for each purpose. This will allow whatever learning there is in production to be applied to the spare engines as well as the installed engines. No parametric model was obtained in this study to enable an early planner to predict the appropriate spares ratio for a particular application.

OTHER COSTS

Other operating and support costs besides depot and base maintenance (and fuel and attrition) contribute to the total life-cycle cost of an engine. They include:

1. ECP and modification costs
2. Transporation
3. AGE and tooling
4. Management
5. Training
6. Fuel
7. Attrition
8. Facilities

The CIP includes the engineering design and testing of hardware changes for engines in operational use. The costs of the new parts are a separate procurement and may be contained in the weapon-system BP1100 account or possibly also in the BP1500 account. Thus, it is not clear what modification parts costs have or have not been adequately captured. It would appear that if an engine is forced to return to the depot prior to an overhaul, then modification kit parts would come under BP1100. If, on the other hand, the engine is allowed to remain in the field until it comes back to the depot through normal processes, either by failing or by reaching MTBO, then modifications to be incorporated in the engine at the depot may actually have been purchased under the BP1500 investment account. Thus, it is difficult to truly identify costs associated with modifications. And because the engine-related costs in BP1100 are not currently broken out of the overall weapon-system account, it is a laborious task to identify the BP1100 in the depot account. It does appear that the labor installation cost is captured at the depot within the HO36B data system, and at the base by the propulsion shop people. What is not captured, or at least fully captured, are the costs of the new parts. It is recommended that the engine manager obtain these costs in the future. As a convenience, they could probably be assessed against the overall cost at the depot (even though installed in the field), since the cost is an investment cost and would be under the engine manager's account, and therefore not a cost that the base incurs. What is important is to keep track of the parts and maintain the identity of the cost for those parts. In addition, modifications must be tracked, not only through AFLC after operational use, but also right from the beginning at the SPO as soon as modifications begin with development and testing and initial operational experience. Mod-kit costs for engines should be obtained by the year purchased, even though the kits are not necessarily installed in that year. The main thing is that costs are included and there is a consistent procedure.

With regard to transportation, data indicate that the cost of shipping engines from a base to a depot and back will not exceed 1 to 2 percent of the depot cost for overhaul; the cost therefore reflects significantly less than 1 percent of the total life-cycle cost. An engine manager should still be alert to saving costs and reducing shipping time, since he is dealing with a very valuable asset.

The procurement of aerospace ground equipment and tooling, and the recurring investment in parts to maintain them, are currently small compared with the total life-cycle cost of the weapon system: They too should account for significantly less than 1 percent of the total cost. For the new operational F-15 wing at Langley

Air Force Base, for instance, an investment of $3.2 million was required for the supporting ground equipment and tooling for the propulsion shop, whereas the value of the engines in the inventory for that wing alone will exceed $300 million. If engine health monitoring systems come into use on a wide scale, and are considered peculiar support equipment, this factor may grow for future engines.

The management of technical data—the paperwork associated with changes to the engine and maintaining parts inventory at the bases and at the depot—is also small relative to total life-cycle cost: again, significantly less than 1 percent.

In the propulsion shop, most personnel training will be on-the-job training. A graduate of an engine mechanic school, fresh from Air Force basic training and assigned to his first base, is a 3-level mechanic. He then obtains on-the-job training and experience by working under the direction of 5- and 7-level specialists, and is expected to become a 5-level specialist within a year. OJT is not specifically broken out in 66-1. All entries are considered actual work whether OJT was happening or not. In terms of training cost, this study does not consider initial training for replacement of attrition due to manpower turnover in the Air Force. Turnover can be as high as 20 percent per year, and this training cost will vary from weapon system to weapon system. It could range anywhere from 5 to 15 percent of a weapon system's total cost if all appropriate training charges are levied against it. This study does not charge these training costs against particular weapon systems.

Fuel cost must be identified separately. It is, of course, highly significant to the total cost of the weapon system and dependent upon the performance parameters chosen for the engine; but it is also highly dependent upon the mission profile and use of the weapon system, and thus must be identified separately and not lumped into some aggregate engine operating and maintenance cost at a base.

Aircraft attrition also should be identified separately because of the highly dependent attrition rate concerning weapon-system configuration, the number of engines on the aircraft, and its mission. For instance, it is expected that a single-engine aircraft will have a higher attrition than a twin-engine aircraft, and a fighter will have higher attrition than a multi-engine transport aircraft. This cost must also be clearly identified separately.

Facilities costs will depend strictly on the system's peculiar needs and the availability of comparable facilities in the Air Force. Occasionally, new facilities are required to replace those becoming obsolete; but new systems do not necessarily require new facilities. The cost analyst must judge whether new facilities would have been bought in any case, regardless of the weapon system using them.

When all of the above costs are included in a total weapon-system life-cycle cost analysis (excluding fuel and attrition, and initial training replacement), it would appear that they currently add not more than 5 percent to all costs previously discussed. In other words, increasing the total life-cycle cost for an engine by 5 percent should encompass all of the costs identified here.

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